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Aquatic Plant Control Research Program

Studies of Water Movement in Vegetated and Unvegetated Littoral Areas

by Craig S. Smith. William F. James,
John W. Barko, Harry L. Eakin

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Prepared for Headquarters, U.S. Army Corps of Engineers

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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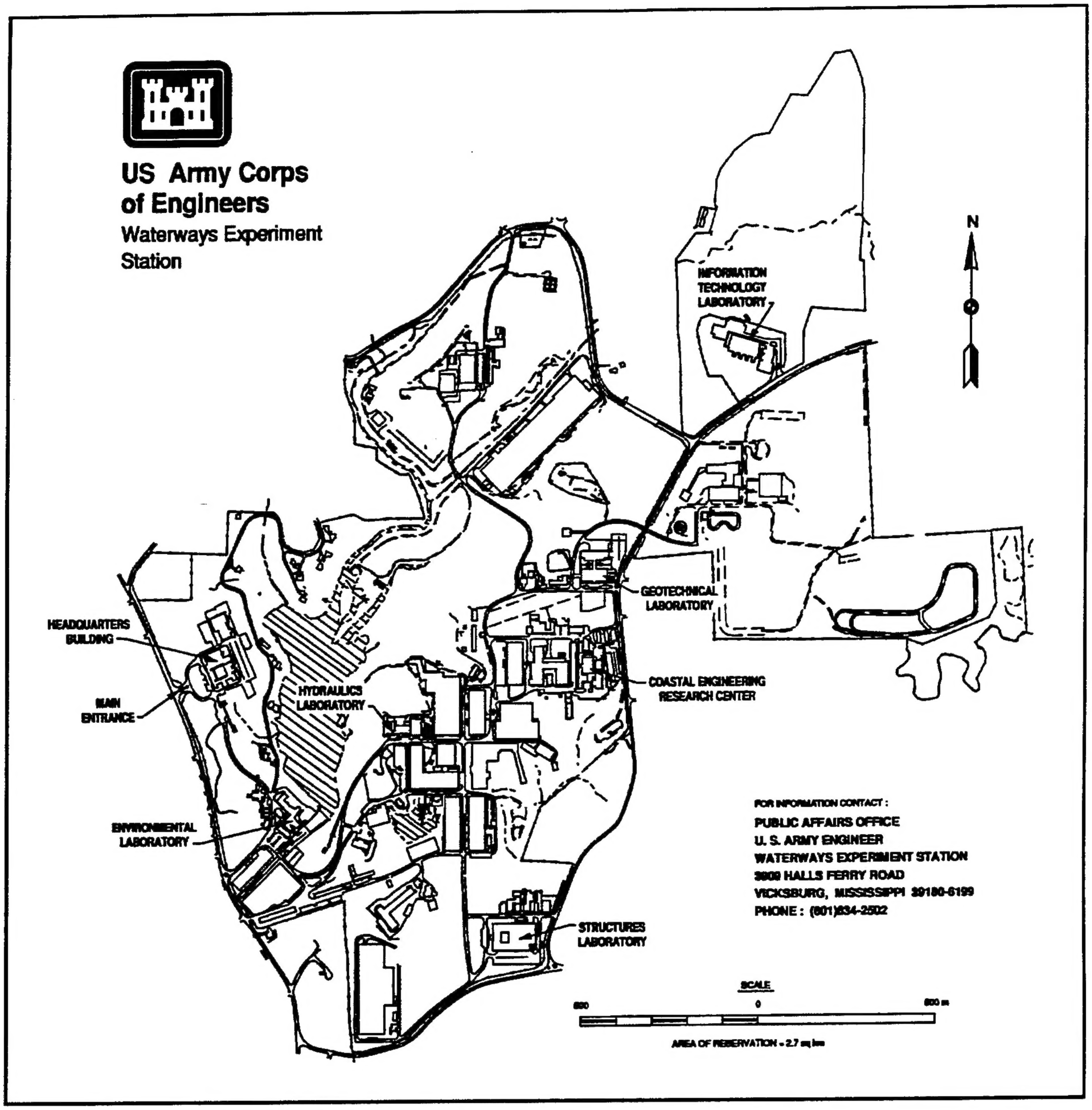

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP), Work Unit 32405. The APCRP is sponsored by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation No. 96X3122, Construction General. The APCRP is managed under the Environmental Resources Research and Assistance Programs (ERRAP), Mr. J. L. Decell, Manager. Mr. Robert C. Gunkel, Jr., was Assistant Manager, ERRAP, for the APCRP. Program Monitor during this study was Ms. Denise White, HQUSACE.

This investigation was conducted under the general supervision of Dr. John W. Keeley, Director, EL, and Mr. Donald L. Robey, Chief, Environmental Processes and Effects Division, EL, and under the direct supervision of Dr. Richard E. Price, Acting Chief, Ecosystem Processes and Effects Branch, EL.

The report was prepared by Dr. Craig S. Smith, Mr. William F. James, Dr. John W. Barko, and Mr. Harry L. Eakin, WES. Dr. H. Stefan of the University of Minnesota and Mr. Michael L. Schneider of WES provided helpful information on convective exchange processes. Messrs. L. Albrightson, R. Charbonneau, and D. Dressel, and Mses. S. Dixon, A. Niccum, and E. Zimmer of the WES Eau Galle Aquatic Ecosystem Research Facility assisted in the Eau Galle Reservoir study. Messrs. Douglas Murphy, David Brewster, and Mark Dowdy, TVA, and Kevin Pigott, AScI Corporation, assisted in studies of Guntersville Reservoir. The report was reviewed by Mr. R. Michael Stewart and Mr. Schneider.

Director of WES during publication of this report was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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1 General Introduction

Water circulation within aquatic plant beds and between plant beds and adjacent open water zones has important implications for both areas. Water movement mediates the exchange of dissolved and suspended materials, including nutrients, dissolved oxygen, and suspended sediments. These exchanges are particularly important since they occur between areas dominated by different ecological life forms and processes. The littoral zone can be an important source of phosphorus (P) and other nutrients to the pelagic zone of lakes and reservoirs. Rooted submersed macrophytes mobilize sediment P by root uptake and senescence (Barko and Smart 1980; Carpenter 1980; Smith and Adams 1986). Macrophytes can also influence the release of nutrients from sediments by influencing pH and other environmental variables. Increasing pH in the water column caused by macrophyte photosynthesis stimulates P release from aerobic sediments through enhanced ligand exchange with iron hydroxide particles (Drake and Heaney 1987). Phosphorus and other nutrients mobilized by either of these mechanisms can then be carried from vegetated regions to nearby open water areas. By influencing water movements, macrophytes also influence sedimentation (James and Barko 1990; Petticrew and Kalff 1991), which in turn affects nutrient availability in the sediments. Typically, sedimentation rates are reduced within the center of macrophyte beds (Eakin and Barko 1989), although they can be elevated on the edges.

Water circulation through plant beds is also a primary determinant of the contact time of herbicides applied to control submersed macrophytes. Since successful control of plants by herbicides depends on maintaining adequate concentrations for sufficient time periods, rates of water circulation determine which herbicides can be used, at what rates they need to be applied, and whether or not they will successfully provide control.

A variety of forces influence water movement within and through aquatic plant beds. These include wind, convection, and advection (currents driven by inflows or outflows). In reservoirs, water level fluctuations resulting from changes in discharge can move water into and out of shallow areas. The importance of these mechanisms will vary, depending on such factors as sheltering and morphometry. Even in relatively small lakes, wind-driven circulation can produce water residence times in the littoral zone of less than a day (Weiler 1978). Convective circulation may be a particularly important water exchange mechanism in wind-sheltered littoral regions, because it can occur in

the complete absence of wind (Stefan, Horsch, and Barko 1989; James and Barko 1991a).

Recent investigations have shown that convective circulation is a potentially important mechanism for the horizontal exchange of nutrients and other substances between littoral and pelagic zones (Stefan, Horsch, and Barko 1989; James and Barko 1991a,b) and between side embayments and the main basin of reservoirs (Monismith, Imberger, and Morison 1990). Convective circulation is driven by horizontal water temperature (and density) gradients that develop when adjacent shallow and deep regions with differing surface-to-volume ratios are heated or cooled (Figure 1). During daytime heating, water in shallow regions heats more rapidly than in deeper regions (i.e., differential heating), resulting in horizontal movement of shallow water as a surface flow over cooler water in the deep region (Monismith, Imberger, and Morison 1990). During nighttime cooling, the opposite pattern occurs. Water in shallow regions cools more rapidly than in deeper regions (i.e., differential cooling), resulting in horizontal movement of shallow water as an underflow below warmer water in the deep region, until a similar density stratum is encountered in the water column (Monismith, Imberger, and Morison 1990).

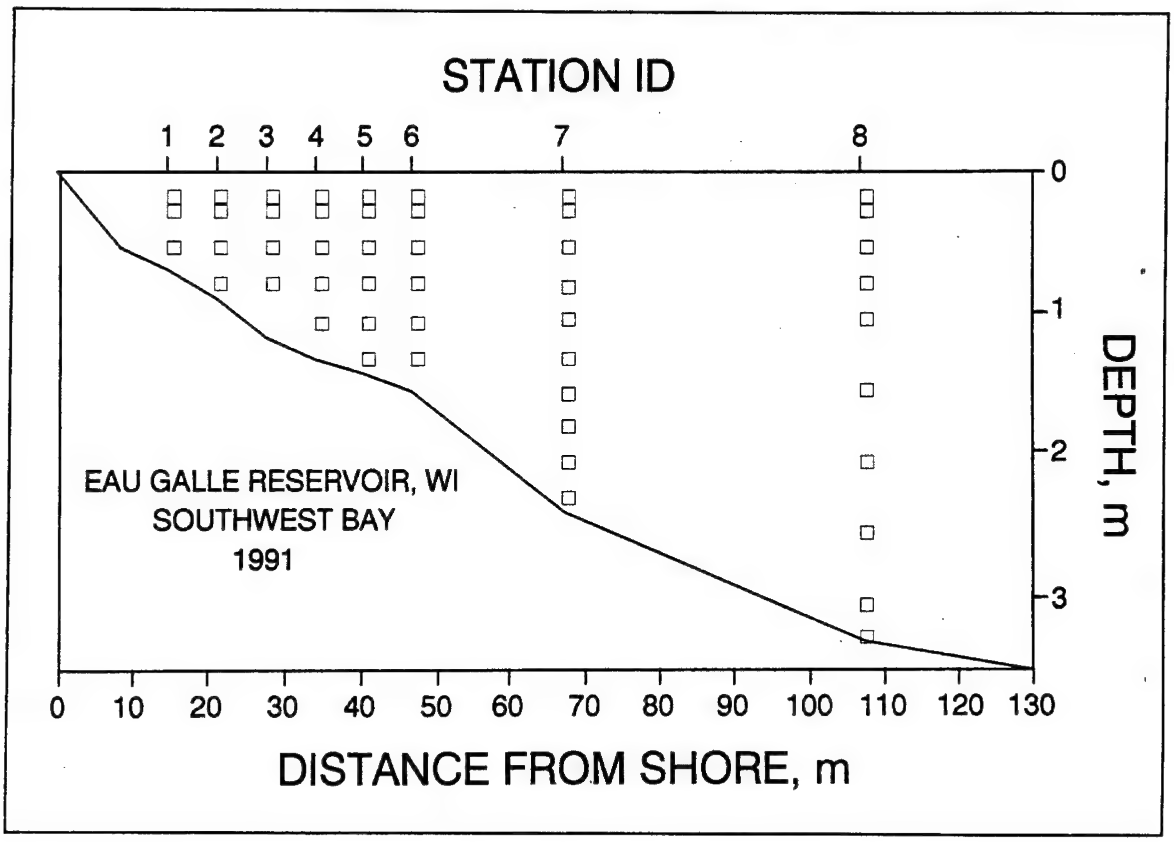

Figure 1. Thermistor locations in southwest embayment of Eau Galle Reservoir

As the size of water bodies increases and sheltering decreases, the importance of wind-driven circulation increases. In shallow embayments of larger

water bodies, patterns of circulation are likely determined by both convection and wind stress. Several types of wind effects are likely. Wind velocity drives vertical mixing and therefore determines the depth of the surface mixed layer. On calm days, surface waters can become intensely stratified, while they may become almost completely destratified on windy days. Wind-driven currents also redistribute heated surface water, affecting the development of the horizontal temperature gradients that drive convection (James and Barko 1991b).

Wind direction would be expected to determine the nature of the interaction between wind- and convection-driven currents. Winds driving water in the same direction as convection can be expected to produce substantially greater water movements than that caused by convective transport alone. Winds opposing convective circulation may facilitate the development of substantial thermal gradients while retarding convective circulation. Winds moving water laterally across thermal gradients can potentially produce complex circulation patterns.

Submersed vegetation has the potential to greatly influence water circulation rates and patterns. Dense beds of submersed plants add considerable structure and therefore hydraulic resistance to the water column (Fonseca et al. 1982). Plant biomass can also potentially influence thermal stratification and vertical mixing because of the interception of light energy by plant parts as well as their inherent flow resistance. Depending on the plant species, the vertical distribution of light absorption and maximum resistance varies considerably. For example, species such as Eurasian watermilfoil that form a dense canopy at the surface above relatively leafless stems impede flow most in surface layers. Species forming dense surface canopies would also be expected to produce a relatively large increase in thermal stratification.

This report describes several related studies of water circulation in vegetated and unvegetated littoral areas of Eau Galle Reservoir, Wisconsin, and Guntersville Reservoir, Alabama.

2 Convective Water Exchanges During Differential Cooling in the Littoral Zone of Eau Galle Reservoir, Wisconsin[1]

Introduction

The potential for convective water exchanges in an embayment (southwest bay) of Eau Galle Reservoir was examined on a daily basis during the month of August 1991. Specific objectives were to use thermal information collected over close time and space intervals to calculate rates of convective exchange from a heat budget model developed by Stefan, Horsch, and Barko (1989). Estimates were made of convective exchange rates for periods of differential cooling, since the model is applicable only under these thermal conditions. The potential frequency of occurrence of convective exchanges during periods of differential cooling was determined in August 1991.

Methods

A transect (approximately 100 m in length) was established along the slope of the basin of the southwest embayment of Eau Galle Reservoir to examine differential cooling and convective exchanges. Stations for water temperature monitoring in the vegetated littoral zone (Stations 1 to 6) were positioned at 7-m intervals along the transect (Figure 1). Stations in the pelagic zone (Stations 7 and 8) were located at the 2.5-m (65 m from shore) and the 3.5-m (108 m from shore) depths on the transect. Thermistors (OmniData International), which had been precalibrated to the nearest 0.1 °C, were placed at 25-cm-depth intervals at Stations 1 to 7 and at 25- to 50-cm-depth intervals at Station 8. A weather station was established at Station 3 for measurement of

[1] Chapter 2 was written by William F. James and John W. Barko.

net solar radiation, wind speed and direction, air temperature, and relative humidity. Probes for monitoring weather conditions were positioned on a pole approximately 2 m above the reservoir's surface. Instantaneous values for water and air temperature, wind speed and direction, net solar radiation, and relative humidity were collected at 5-min intervals from 07 to 21 August 1991.

The heat budget model, described by Stefan, Horsch, and Barko (1989), was used to estimate rates of convective exchange (Q) between the littoral and pelagic zones. In general, the model estimates the flux of heat between two adjacent, well-mixed cells located on a littoral slope (Figure 2). Since h2 > h1, the water temperature in Cell 1 will be less than the water temperature in cell 2 (T1 < T2) during cooling periods (i.e., differential cooling).

$$Q = ((A2\ V1\ dT1/dt) - (A1\ V2\ dT2/dt))/((T2 - T1)(A1 + A2))$$

Q = Convective Exchange Rate, m^3/m s
A = Surface Area, m^2/m
V = Volume, m^3/m (Ah)
T = Temperature, C

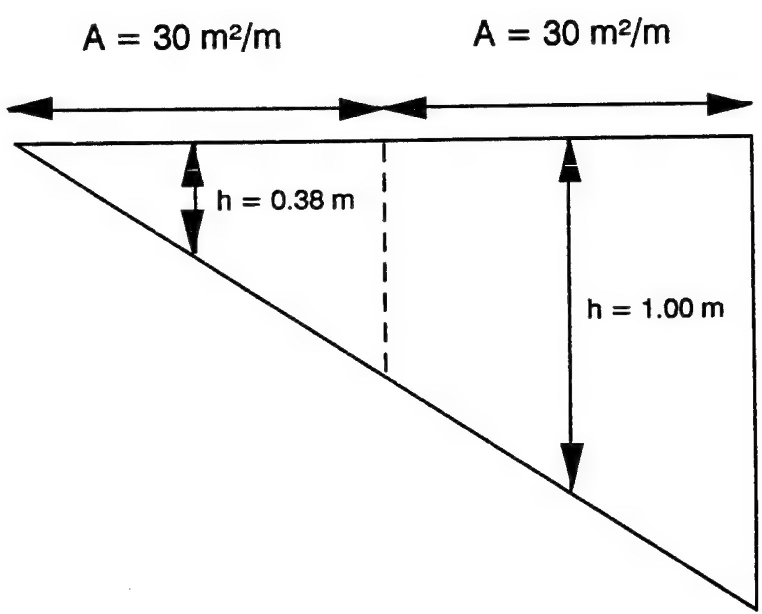

Figure 2. Heat budget equation for estimating convective exchanges during differential cooling and conceptual division of littoral zone into two adjacent cells

Under these unstable thermal conditions, exchange flows will develop naturally. These can be described by changes in water temperature.

For the model, the littoral zone of the southwest bay in Eau Galle Reservoir was divided conceptually into two adjacent cells, each having a particular geometry and thermal regime (Figure 2). Water temperature profiles from Station 1, located nearest the shoreline, and Station 5, located near the littoral-pelagic interface, were used to represent Cells 1 and 2, respectively. Rates of convective exchange between Stations 1 and 5 were estimated at 5-min intervals throughout the month of August during periods of differential cooling (i.e., at night). Differential cooling was assumed to be occurring when vertically integrated water temperatures at Station 1 were less than those at Station 5.

Results and Discussion

An example of weather conditions giving rise to differential cooling and convective exchange occurred during the night of 18-19 August. During this period, air temperatures cooled from a maximum of 20.6 °C at 1300 hr on 18 August to 9.4 °C at 0500 hr on 19 August (Figure 3a). The potential for convective exchange was great, as surface water temperatures cooled much more rapidly at Station 1 than at Station 5 during the night on these dates, resulting in a 1.3 °C differential between the two stations by 0600 hr on 19 August (Figure 3b). With the exception of some minor breezes, wind speeds were zero from 2000 hr on 18 August to 0800 hr on 19 August (Figure 3c). Wind-generated water movement was, thus, probably minor in the embayment during that particular night. By 0200 hr on 19 August, strong horizontal water temperature gradients had developed between Stations 1 and 5 in the littoral zone as a result of differential cooling (Figure 4a). In the pelagic zone, water temperatures were uniform in the upper 2 m of the water column and stratified vertically below this depth. Movement of cooler littoral water as an underflow toward the pelagic zone was suggested by the strong downward slant of the 22.2 °C contour line at 0200 hr (Figure 4a). Intrusion of the underflow current into the pelagic water column at about the 2-m depth was suggested by the position of the 21.4 °C isotherm at 0800 hr (Figure 4b). A return surface flow moving from the pelagic zone toward the littoral zone was clearly evident at 0800 hr, as water temperature contours (ranging from 21.4 to 19.4 °C) in the surface waters slanted toward Station 1 (Figure 4b).

Detailed movement of the underflow down the littoral slope during convective exchange was observed from a time series of vertical water temperature profiles at Stations 1 and 5 during the night of 18-19 August (Figure 5). During the early stages of water column cooling, water temperatures at Station 1 became uniform vertically and cooled steadily between 2000 and 2300 hr (Figure 5). As the night progressed, however, intrusion of cooler water was observed at the bottom of Station 1 at about 2230 hr, an apparent result of an underflow current that originated upstream of Station 1. The underflow

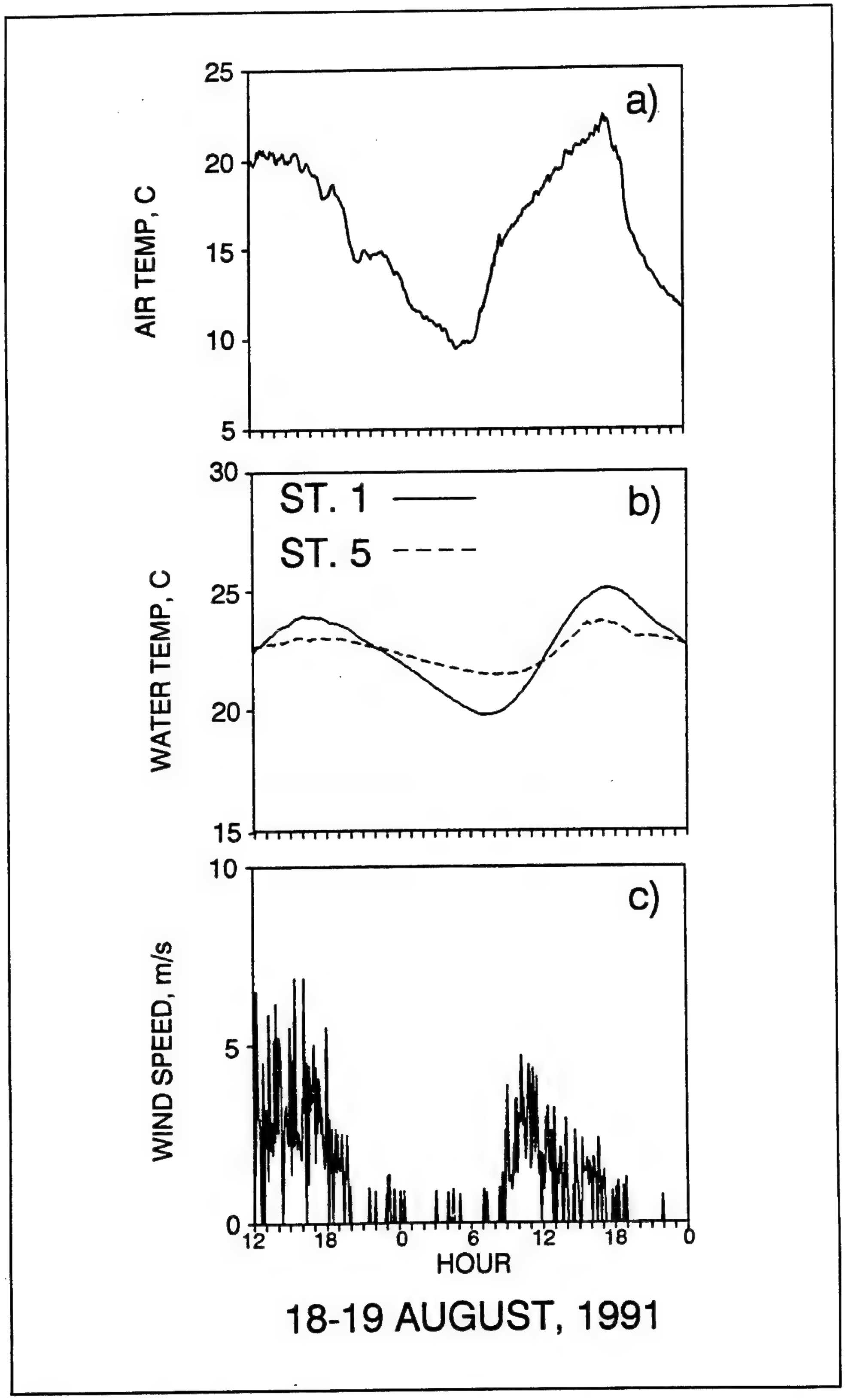

Figure 3. Variations in (a) air temperature, (b) surface water temperature gradients at Stations 1 and 5, and (c) wind velocity between 1200 hr on 18 August and 2400 hr on 19 August 1991

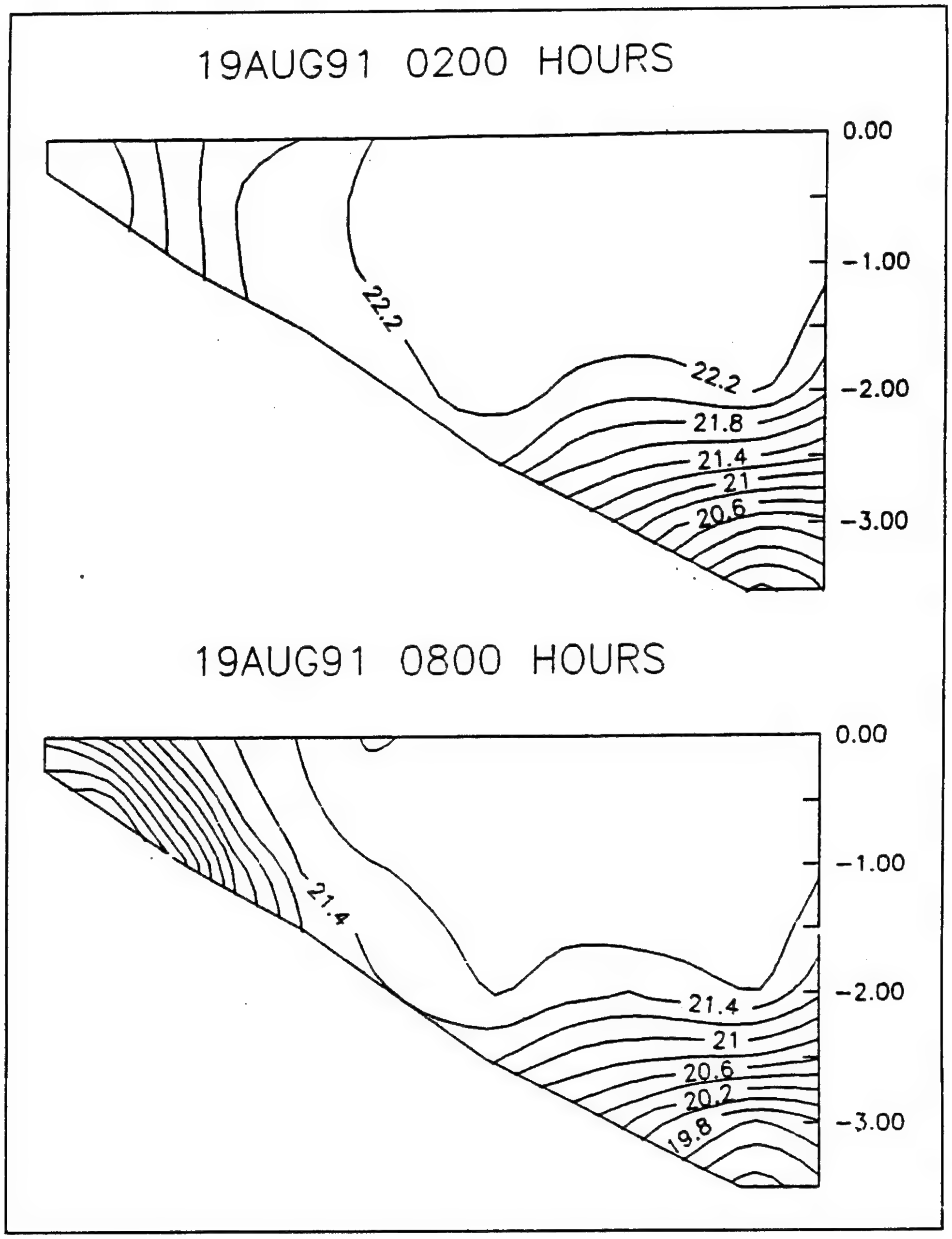

Figure 4. Longitudinal and vertical variations in water temperature (°C) at 0200 hr and 0800 hr on 19 August 1991

reached Station 5, located 28 m down the transect, about 4 hr later, as suggested by the more rapid cooling of the bottom waters than the surface waters at this station at about 0230 hr (Figure 5). A flow velocity of 2 mm/sec or 7 m/hr was estimated based on this information. From earlier research (James and Barko 1991a,b), the vertical expanse of underflows generated during convective exchanges was found to be ~ 0.25 m. Assuming a similar vertical expanse for the underflow that developed during 18-19 August, an areal convective exchange rate of 0.0005 m^3/m sec was estimated.

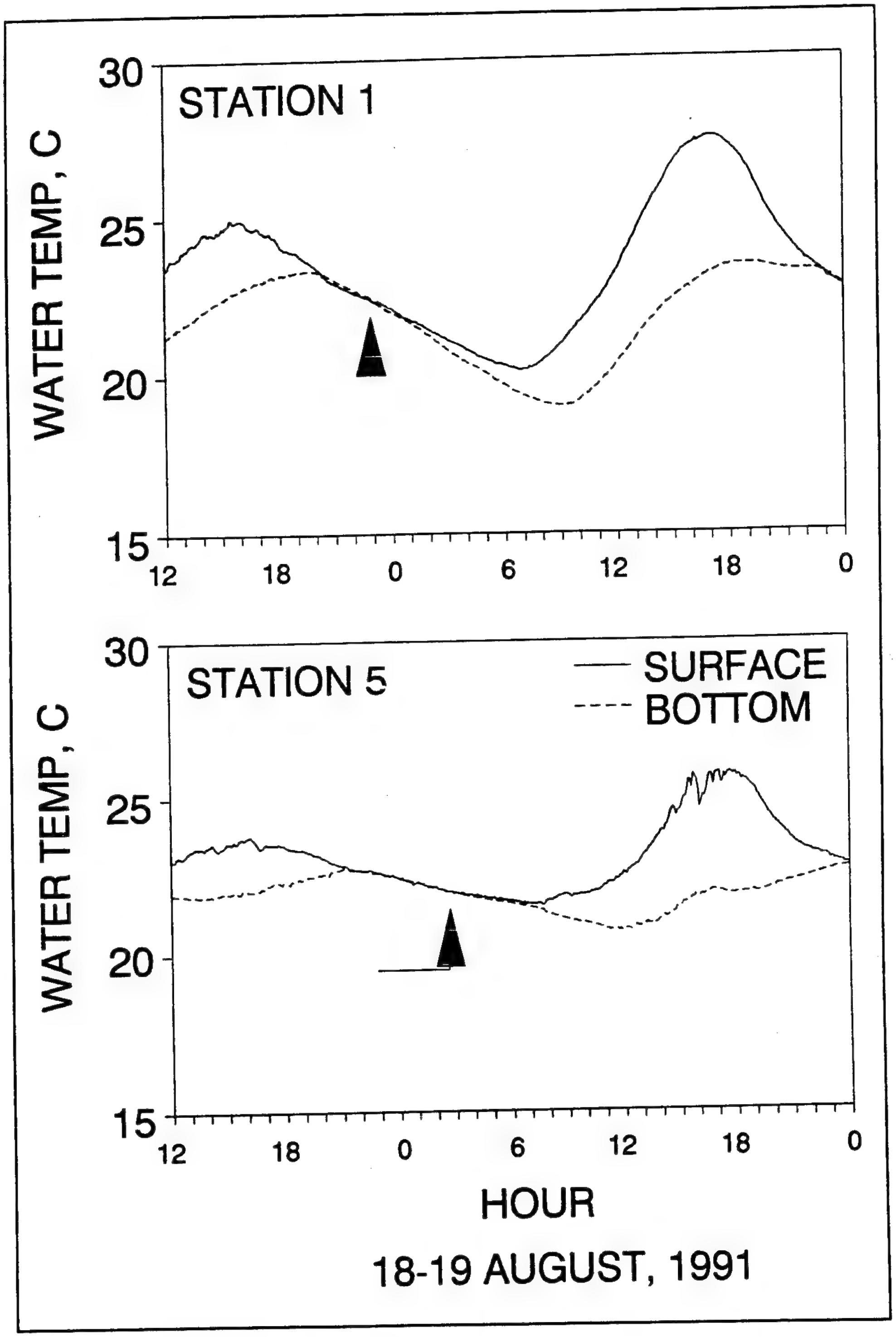

Figure 5. Variations in water temperature at Station 1 (upper) and Station 5 (lower) on 18-19 August 1991

A mean areal convective exchange rate of about 0.0006 m^3/m sec (Figure 6) was calculated from the heat budget model of Stefan, Horsch, and Barko (1989) for the time period 0000-1000 hr on 19 August, which was

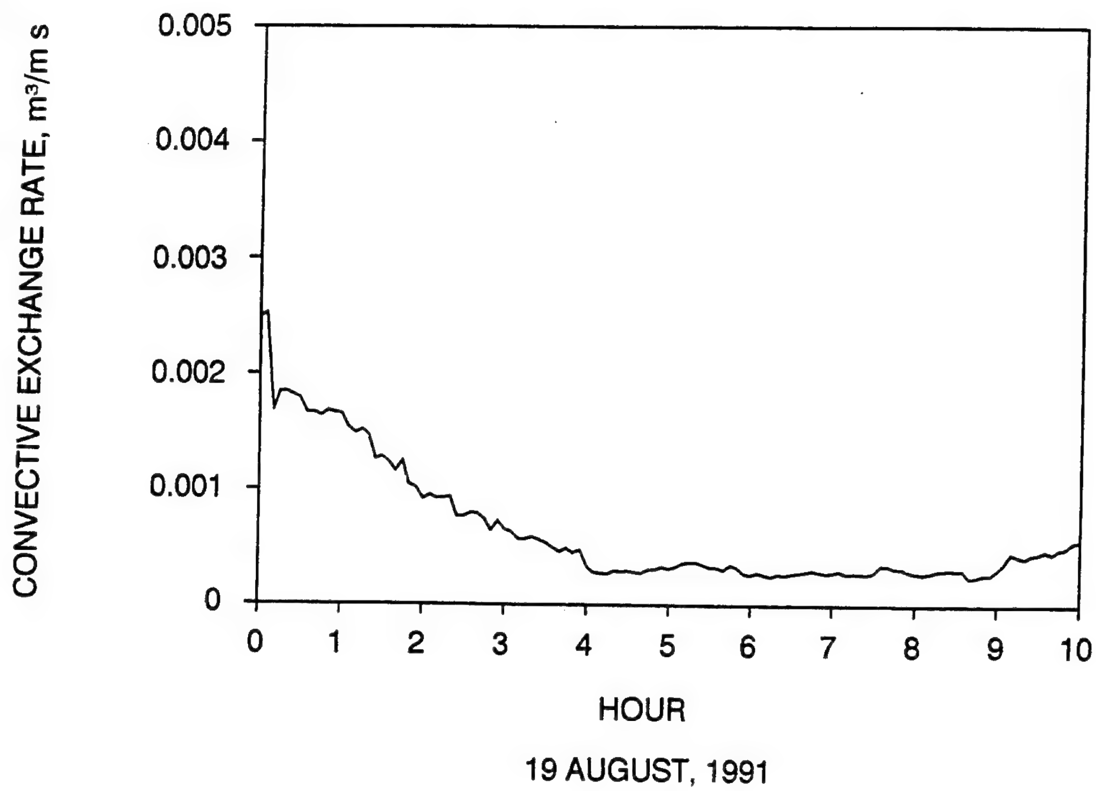

Figure 6. Variations in areal convective exchange rates between 0000 and 1000 hr on 19 August 1991. Rates were smoothed by determining a running average over a 1-hr period at 5-min intervals

similar to the areal convective exchange rate estimated from the examination of the time series of vertical water temperature profiles at Stations 1 and 5 for the same date (Figure 5). In general, the heat budget model estimated relatively high areal convective exchange rates during the onset of differential cooling on 19 August (0000-0200 hr; Figure 6). Areal convective exchange rates (i.e., at 5-min intervals) then declined to <0.001 m^3/m sec by 0330 hr and exhibited minor fluctuation until 1000 hr on 19 August.

The heat budget model was used to estimate mean areal convective exchange rates during periods of differential cooling for nearly the entire month of August (7 to 21 August). Differential cooling occurred on every night of the study, and mean areal convective exchange rates ranged from 0.00047 m^3/m sec on 15 August to 0.00088 m^3/m sec on 13 August (Figure 7). A grand mean convective exchange rate of 0.00066 m^3/m sec was determined for the month of August 1991, which was comparable with the grand mean convective exchange rate of 0.0005 m^3/m sec estimated for the summer of 1989 (June - August) using Rhodamine WT dye movement as a surrogate for water exchange (James and Barko 1991b). The similarity in rates between years suggests that the heat budget model provides a good estimate of convective exchange rates for this reservoir.

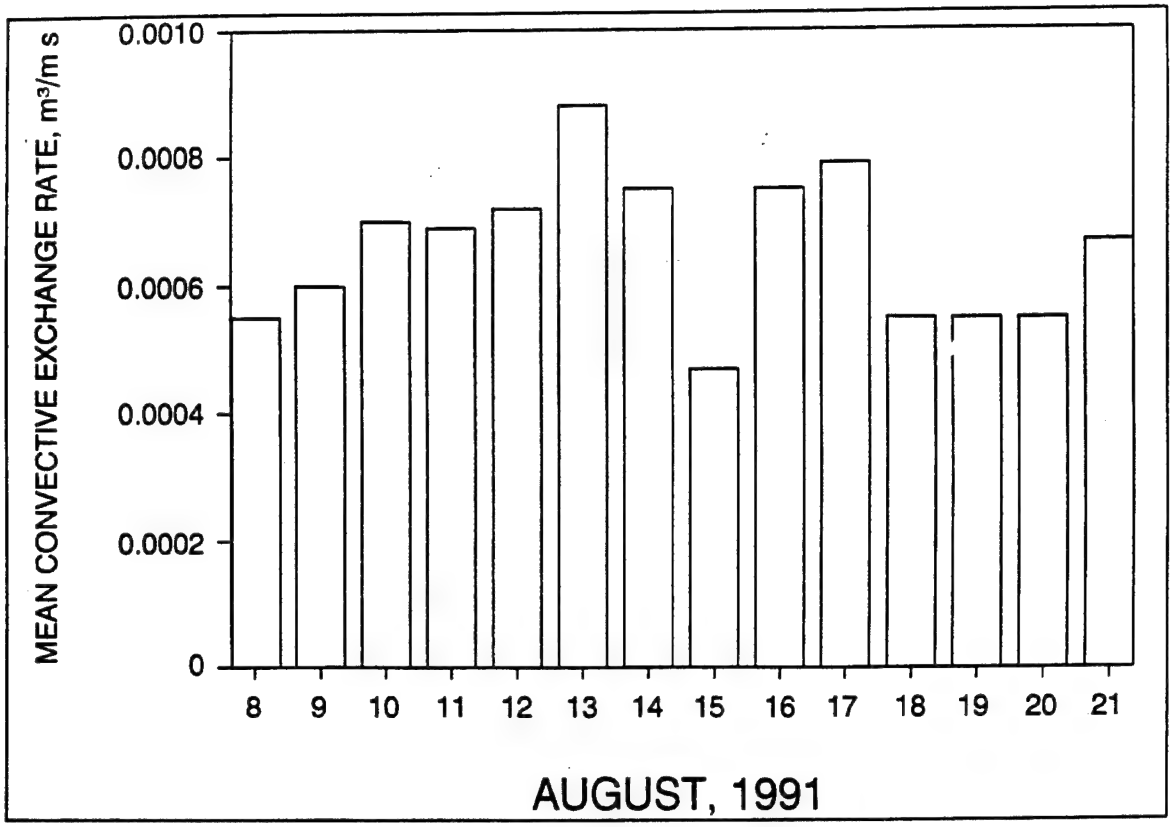

Figure 7. Mean areal convective exchange rate during periods of differential cooling for the period 08 to 21 August 1991

Wind velocities were essentially zero throughout the nighttime periods during the study, with the exception of the nights of 07 and 16 August 1991 (Figure 8). Thus, convective exchanges were probably the dominant means of horizontal transport in this embayment at night during the month of August. A theoretical hydraulic residence time of water in the littoral zone of this embayment (i.e., ~ 10,000 m^3) of only about 1 day was estimated during these periods of differential cooling and convective exchange, which is much more rapid than the reservoirwide theoretical residence time of >30 days (James 1991).

The results of this study have several implications for aquatic plant management. First, convective exchanges need to be considered as a potentially important mechanism for the horizontal transport of solutes between littoral and pelagic zones. Even in the complete absence of wind, the residence time for water in the southwest embayment of Eau Galle Reservoir is low, because of convective exchanges. Thus, herbicide application strategies must consider these short residence times when evaluating interactions between herbicide concentration and exposure times (Netherland, Green, and Getsinger 1991) and the movement of herbicides from target areas to open water sites via convective as well as wind-generated water exchange. Second, horizontal movement of soluble nutrients originating from decaying macrophytes to the pelagic zone via convective exchanges may stimulate undesirable algal blooms after a herbicide treatment.

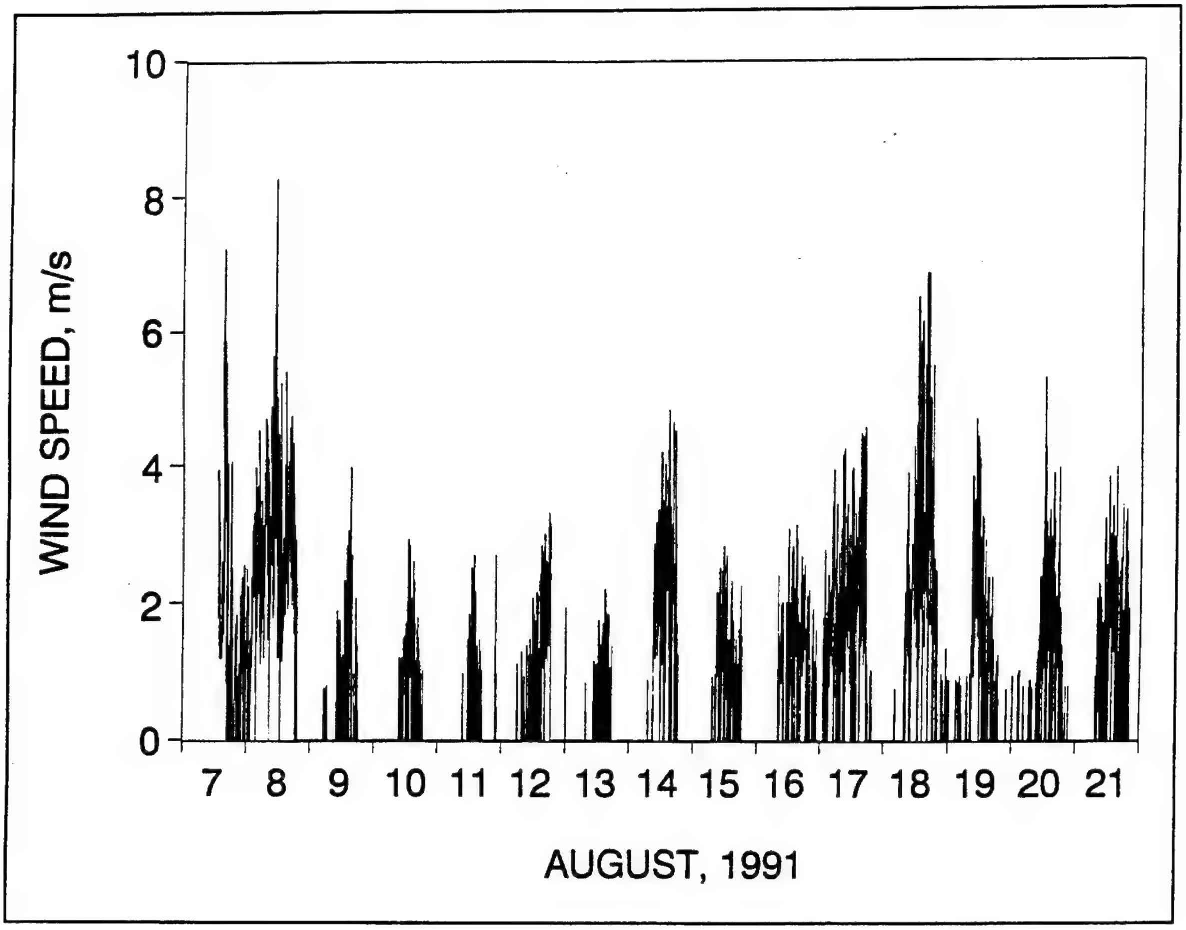

Figure 8. Variations in wind velocity from 08 through 21 August 1991

3 Convective Water Exchanges During Differential Cooling and Heating in the Minky Creek Embayment of Guntersville Reservoir: Implications for Dissolved Constituent Transport[1]

Introduction

Differential cooling and heating and resultant convective exchange patterns were examined in an embayment (Minky Creek) of Guntersville Reservoir, Alabama, during September 1990. The reservoir historically has experienced relatively high macrophyte biomass levels (dominated by *Myriophyllum spicatum* and *Hydrilla* sp.) during most years, necessitating control via extensive herbicide application and mechanical means (Bates, Decell, and Swor 1991). Concerns over the potential transport of aquatic herbicides and soluble nutrients originating from decaying macrophytes to undesirable locations (e.g., swimming and fishing areas) led to an examination of water exchange mechanisms that might result in movement of these substances. This chapter describes convective exchange patterns in the Minky Creek embayment and documents the frequency of occurrence of these patterns on a daily basis during the late summer. Vertical and horizontal variations in water temperature were examined to characterize patterns of differential cooling, differential heating, and convective exchanges in this embayment.

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1 Chapter 3 was written by William F. James, John W. Barko, and Harry L. Eakin.

Methods

Guntersville Reservoir, located on the Tennessee River in northeastern Alabama, is a large (27,500 ha) hydropower and flood control impoundment operated by the Tennessee Valley Authority. The Minky Creek embayment of the reservoir, site of the present study, is relatively shallow (maximum depth of 6 m). Until 1990, this embayment exhibited an extensive littoral zone dominated primarily by *M. spicatum*. In 1990, however, macrophyte biomass levels were substantially reduced in this embayment and in other areas of the reservoir as well, because of unknown causes.

A transect was established along the slope of the basin on the northwestern shoreline of the Minky Creek embayment to examine differential cooling and heating patterns (Figure 9). The transect extended from the shore outward approximately 400 m into the embayment. Stations for water temperature monitoring were located at the 1.0- (50 m from shore), 2.0- (125 m from shore), 3.5- (175 m from shore), 5.0 (275 m from shore), and 5.75-m (375 m from shore) depths on the transect. Recording temperature monitors (Omnidata International) were placed on permanently anchored platforms at these

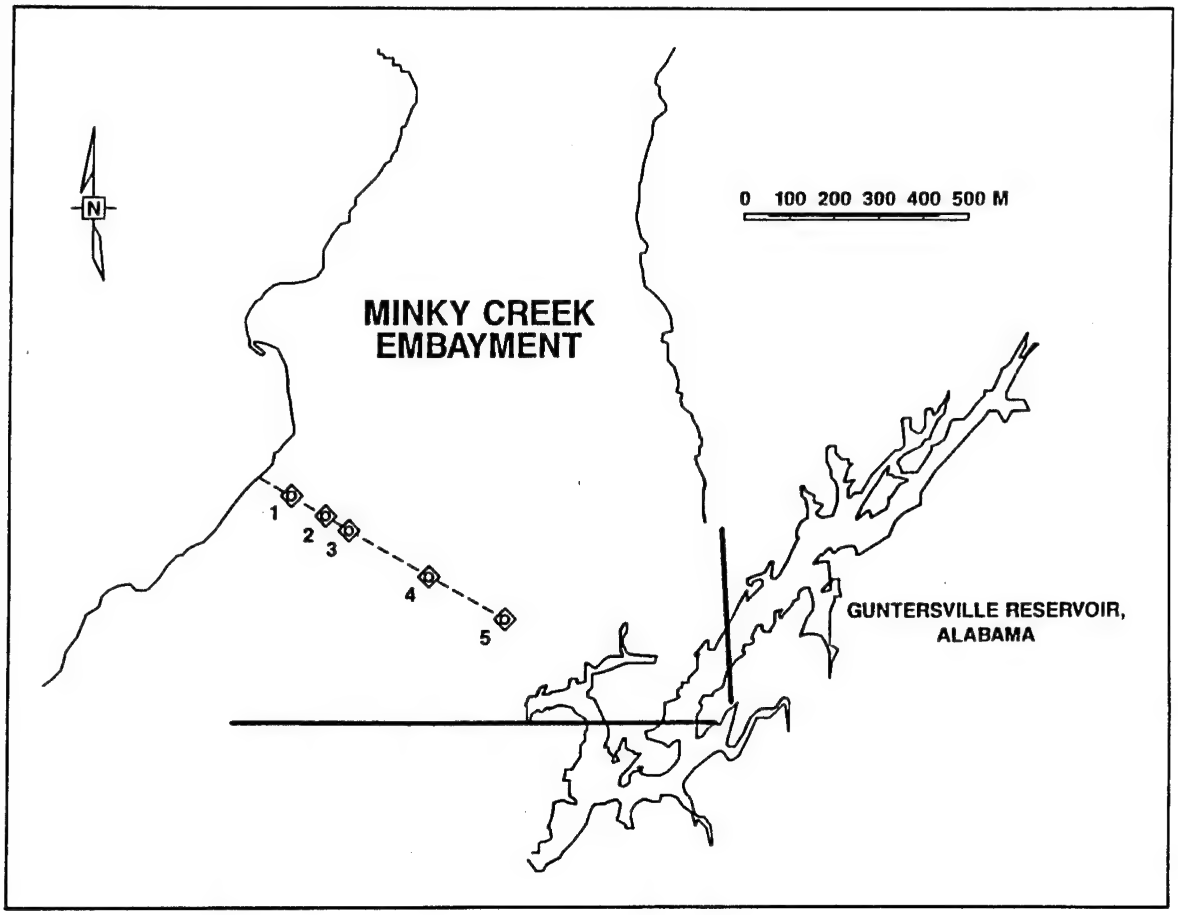

Figure 9. Guntersville Reservoir and thermistor station locations

stations. Instantaneous air and water temperatures were measured every half hour with thermistor probes (Fenwall Model UUT-51J1) calibrated to the nearest 0.1 °C in a constant temperature water bath against a thermometer that had been previously calibrated with a National Bureau of Standards thermometer. The response time of the thermistor probes was 15 sec in still water and 200 sec in still air. Thermistor probes were positioned at 25-cm-depth intervals at Stations 1-3 and at 50-cm intervals at Stations 4-5. Wind speed and direction were measured at Station 1 every 2-min and recorded as an average every half hour using an anemometer and wind vane (Omnidata International, model no. ES-040). Convective exchange patterns were assessed over 2-hr intervals or less by generating water temperature contours over the entire transect using SURFER (version 3.0; Golden Software, Inc.).

Cluster analysis (FASTCLUS; SAS 1988) was used to find general relationships among the depth of the surface mixed layer at shallow stations, wind speed, and horizontal water temperature gradients during differential heating phases. Mean values of these variables over the time period 1200 to 1400 hr were used for the analysis, because thermal gradients were usually well established during this time frame (see Results). Vertical water temperature gradients at Station 2 were chosen to estimate the surface mixed layer depth, because this station had the deepest water column depth within the region of differential heating. The surface mixed layer was estimated from the following equation;

$$h = H - \frac{\int_O^H z \, d\rho/dz \, dz}{\int_O^H d\rho/dz \, dz}$$

where H is the water column depth, $\rho(z)$ is the water density, and z is the depth of a particular stratum (Patterson, Hamblin, and Imberger 1984). Water density was calculated according to the Tennessee Valley Authority (1972).

Results

Differential cooling and heating

The surface waters (i.e., upper 1 m) at Stations 1 and 2 generally cooled and heated more rapidly than other stations on a diel basis, indicating that differential cooling and heating were confined to water column depths ≤2 m along the transect. Horizontal water temperature gradients using the difference in depth-integrated water temperatures (from the upper 1 m of the water column) were calculated between Stations 1 and 5. A negative horizontal water temperature gradient reflected differential cooling (i.e., surface water temperature less at Station 1 than at Station 5), while a positive horizontal water temperature gradient reflected differential heating (i.e., surface water temperature greater at Station 1 than at Station 5). In general, negative horizontal water

temperature gradients were observed during nighttime cooling, while positive horizontal water temperature gradients were observed during daytime heating (Figure 10a).

During periods when the water column exhibited a net daily heat gain (01-08 and 19-21 September; Figure 10b), negative horizontal water temperature gradients decreased to near zero. At these times, peaks in the positive horizontal water temperature gradient were quite high, often exceeding 1 °C. In contrast, during periods of net daily heat loss from the water column (09-18 and 22-23 September; Figure 10b), positive horizontal water temperature gradients generally declined while negative horizontal water temperature gradients increased.

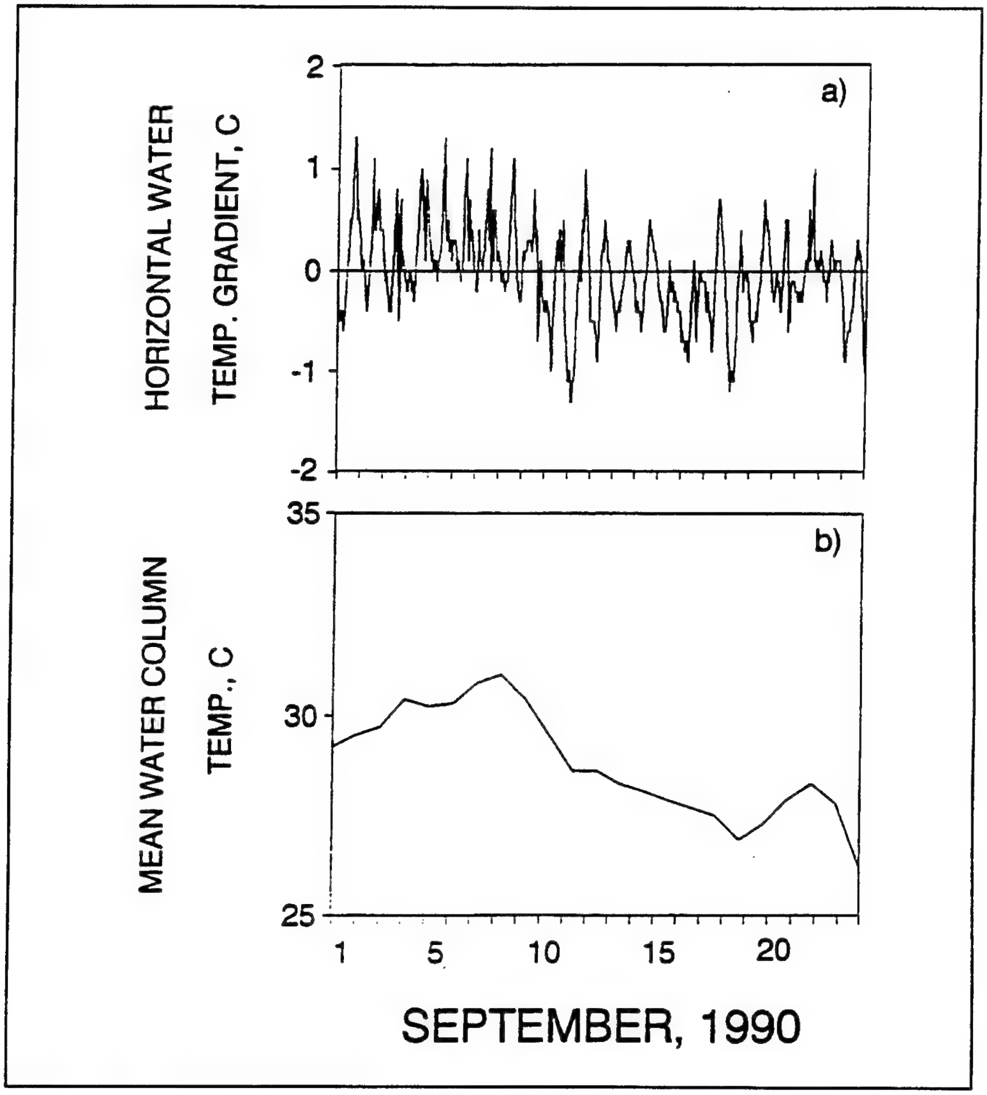

Figure 10. Variations in (a) horizontal water temperature gradients (upper 1 m) between Stations 1 and 5 and (b) mean daily water temperature

Convective exchanges during periods of differential cooling

A good example of conditions giving rise to convective exchange because of differential cooling occurred during the night of 23-24 September. Although water temperatures were nearly uniform vertically at all stations during the night, strong horizontal gradients in water temperature were observed along the transect between Stations 2 and 3 by 2000 hr (Figure 11). At 2400 hr, the water column of Stations 1 and 2 had cooled considerably in relation to deeper stations, and cooler water was observed at the bottom of Stations 3 to 5, suggesting the development of an underflow current (Figure 11). As differential cooling continued during the night, water temperature contours slanted strongly downward from Stations 2 to 4 by 0400 hr, resulting

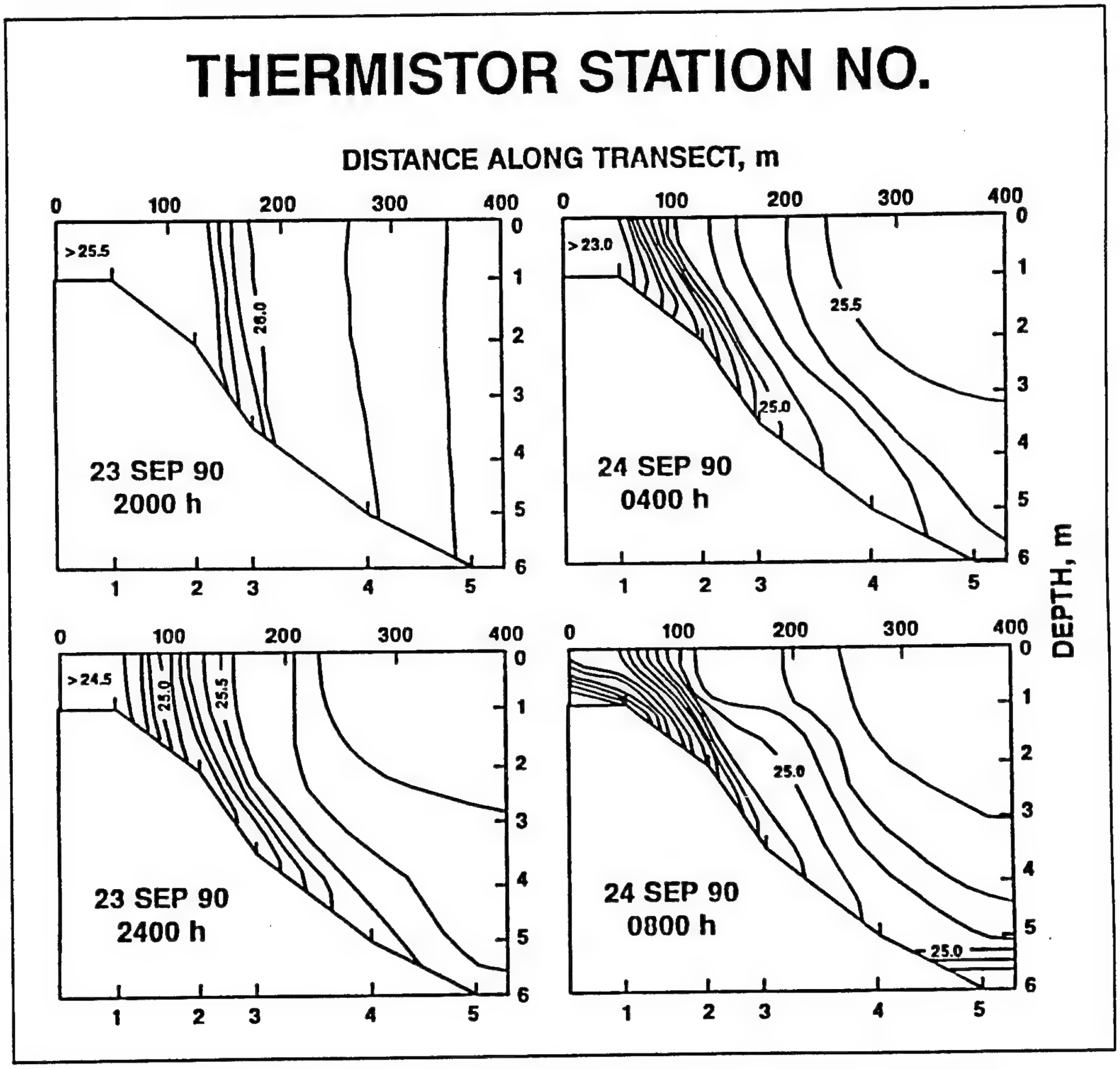

Figure 11. Longitudinal and vertical variations in water temperature (°C) at 2000 and 2400 hr on 23 September and at 0400 and 0800 hr on 24 September 1990

in strong vertical stratification in the bottom waters of Station 3 (Figure 11). Horizontal water temperature gradients also became compressed near the reservoir surface between Stations 1 and 2 at 0400 hr, suggesting the occurrence of a return surface flow toward Station 1. At 0800 hr, the return surface flow of warmer water moving toward Station 1 was clearly evident, as surface temperatures at Stations 1 and 2 increased over those observed at 0400 hr (Figure 11). Periodic heating of the water column was observed frequently (i.e., at 0130, 0330, 0500, 0600, and 0700 hr) during the night at Station 1 (Figure 12), further suggesting the movement of return currents of warm surface water into Station 1. Overall, these patterns in water temperature (i.e., Figure 11) were observed on 13 nights during September, generally when the mean negative horizontal temperature gradient was >0.3 °C, suggesting convective exchange during differential cooling.

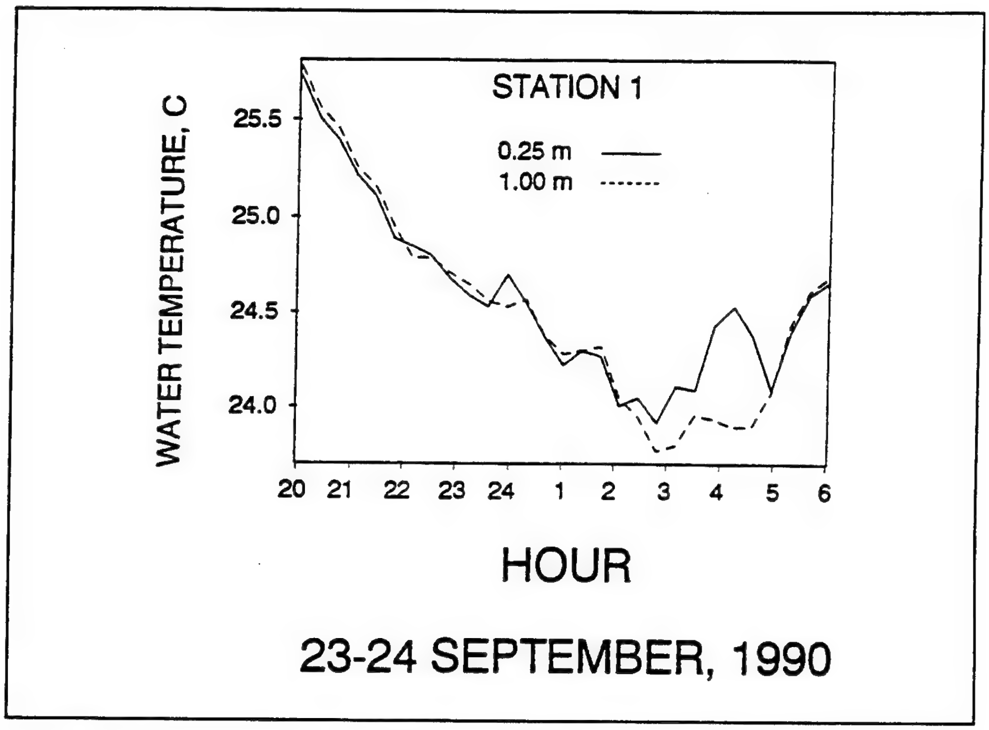

Figure 12. Variations in water temperature at Station 1 between 2000 hour on 23 September and 0600 hr on 24 September 1990

Convective exchanges during periods of differential heating

High wind periods. An example of conditions giving rise to convective exchange because of differential heating during a relatively windy period occurred on 01 September. Winds from the southeast blew steadily between 2 and 3 m sec^{-1} from noon until 2000 hr on this date. At 1400 hr, water temperatures in the upper water column were nearly uniform vertically at Stations 1 and 2; however, vertical stratification developed at several depths in the water column at Stations 4 and 5 (Figure 13). Strong horizontal water temperature

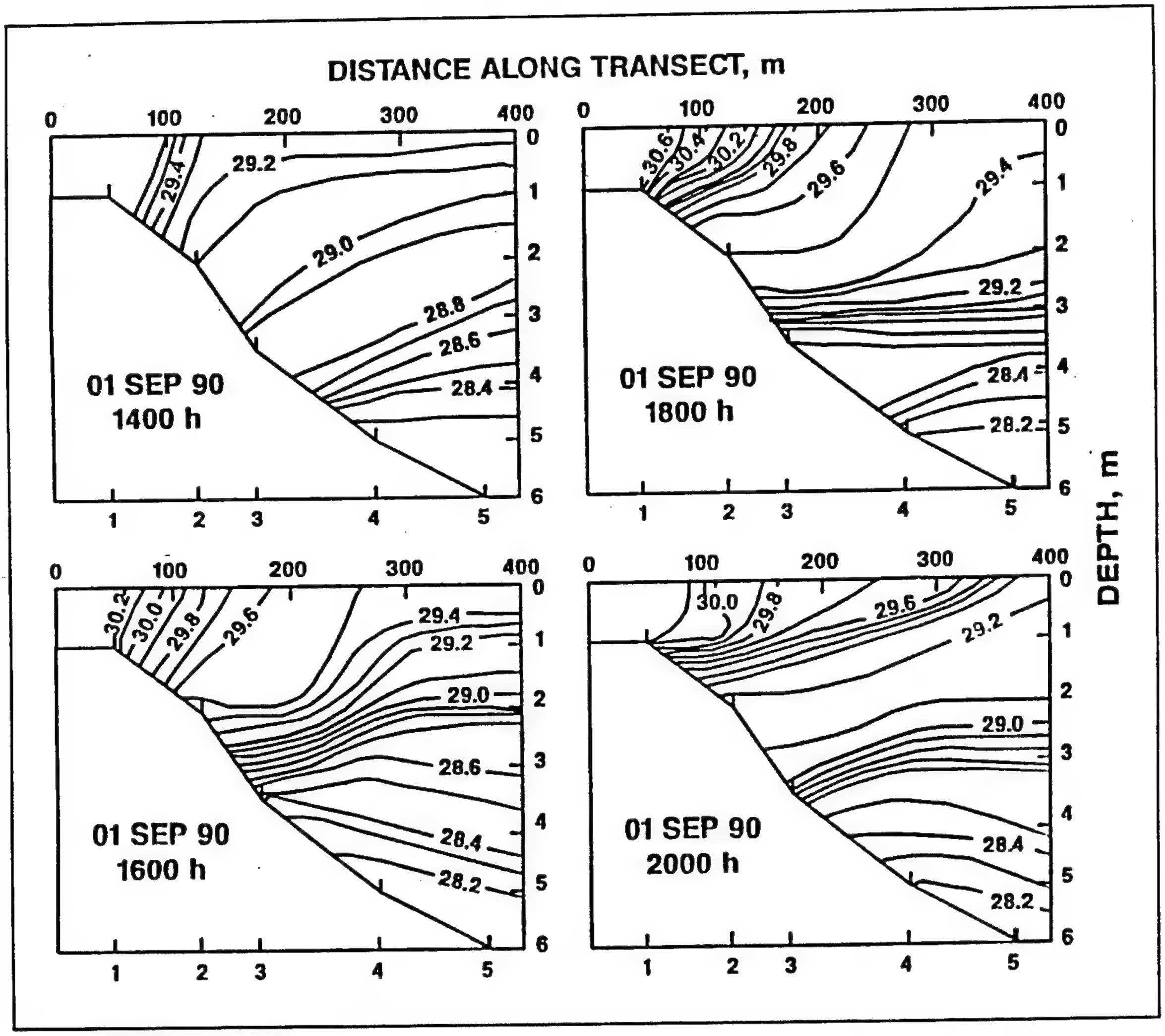

Figure 13. Longitudinal and vertical variations in water temperature (°C) at 1400, 1600, 1800, and 2000 hr on 01 September 1990

gradients were observed between Stations 1 and 2 at this time because of differential heating.

At 1600 hr on 01 September, further differential heating occurred, as water temperatures at Station 1 were nearly 1 °C greater than those in the upper 1 m at Stations 4 and 5 (Figure 13). Movement of a vertically expansive overflow (about 2 m deep) of warmer surface water from the back of the transect toward Station 4 was suggested by the repositioning of the 29.4 °C contour between 1400 and 1600 hr (Figure 13). A strong primary metalimnion (represented by the 28.7 to 29.4 °C contours), positioned between the 0.5- and 2.25-m depths, developed at Stations 4 and 5 at 1600 hr. However, a pronounced downward deflection of the metalimnion (to depths >2 m) occurred at Station 3 in the vicinity of the apparent overflow.

At 1800 hr on 01 September, further movement of an overflow was suggested by changes in the position of the 29.4 to 29.6 °C contours and a

flattening of the primary metalimnion between Stations 3 and 5 (Figure 13). A secondary metalimnion formed at 1800 hr, as horizontal water temperature gradients developed between the reservoir bottom near Station 1 and the water surface at Stations 2 and 3. By 2000 hr, the secondary metalimnion became compressed, because of further movement of surface water, and it extended outward 350 m along the transect (Figure 13). Concomitantly, a return flow of cool water at intermediate depths (i.e., below the secondary metalimnion) was suggested, as the bottom waters at Station 2 cooled by 0.4 °C (i.e., from 29.6 °C at 1800 hr to 29.2 °C at 2000 hr) below the secondary metalimnion (Figure 13).

Moderate wind periods. An example of conditions giving rise to convective exchange because of differential heating during moderate winds occurred on 07 September. The depth of the surface mixed layer (0.68 m) on 07 September was much more shallow than the surface mixed layer depth of >2.0 m observed at 1600 hr on 01 September (Figure 13). This difference in the surface mixed layer coincided with lower wind speeds that fluctuated between 1 and 2.5 m/sec (southwest) throughout much of the afternoon on 07 September and were near zero at 1530 hr.

Despite these differences in conditions, water temperature dynamics on this date (Figure 14) were similar to those observed on 01 September (Figure 13). As an apparent result of differential heating, a shallow surface overflow developed nearshore between 1200 and 1400 hr that moved outward toward Station 5 at 1600 hr. A return flow of cooler water moving from the opposite direction to the bottom of Station 1 was suggested, as water temperatures below the 0.5-m depth decreased by nearly 1 °C at this station between 1500 and 1700 hr (Figure 15).

Low wind periods. An example of water temperature dynamics during low winds occurred on 11 September. On this date, conditions contrasted markedly with conditions encountered during more windy periods described above. A very shallow surface mixed layer of 0.47 m was observed at 1200 hr that extended the length of the transect by 1400 hr (Figure 16). This pattern of a very shallow surface mixed layer coincided with wind speeds of zero from 1000 to 1200 hr and <2 m/sec thereafter.

General patterns in water temperature dynamics during differential heating phases. Based on results of cluster analysis (Table 1), four general patterns were found that could be related to variations in water temperature dynamics during differential heating phases. Pattern 1, exemplified by thermal patterns observed on 11 September, exhibited the lowest mean wind speed and surface mixed-layer depth and a moderate mean horizontal temperature gradient during early afternoon. These conditions occurred on 35 percent of the early afternoons in September (Figure 17). Pattern 2, exemplified by thermal patterns occurring on 07 September, exhibited a mean surface mixed layer of >1.0 m, moderate mean wind speeds, and the highest mean horizontal temperature gradient. These conditions, occurring on 30 percent of the early afternoons, resulted in pronounced cooling of the bottom waters at Station 1 by

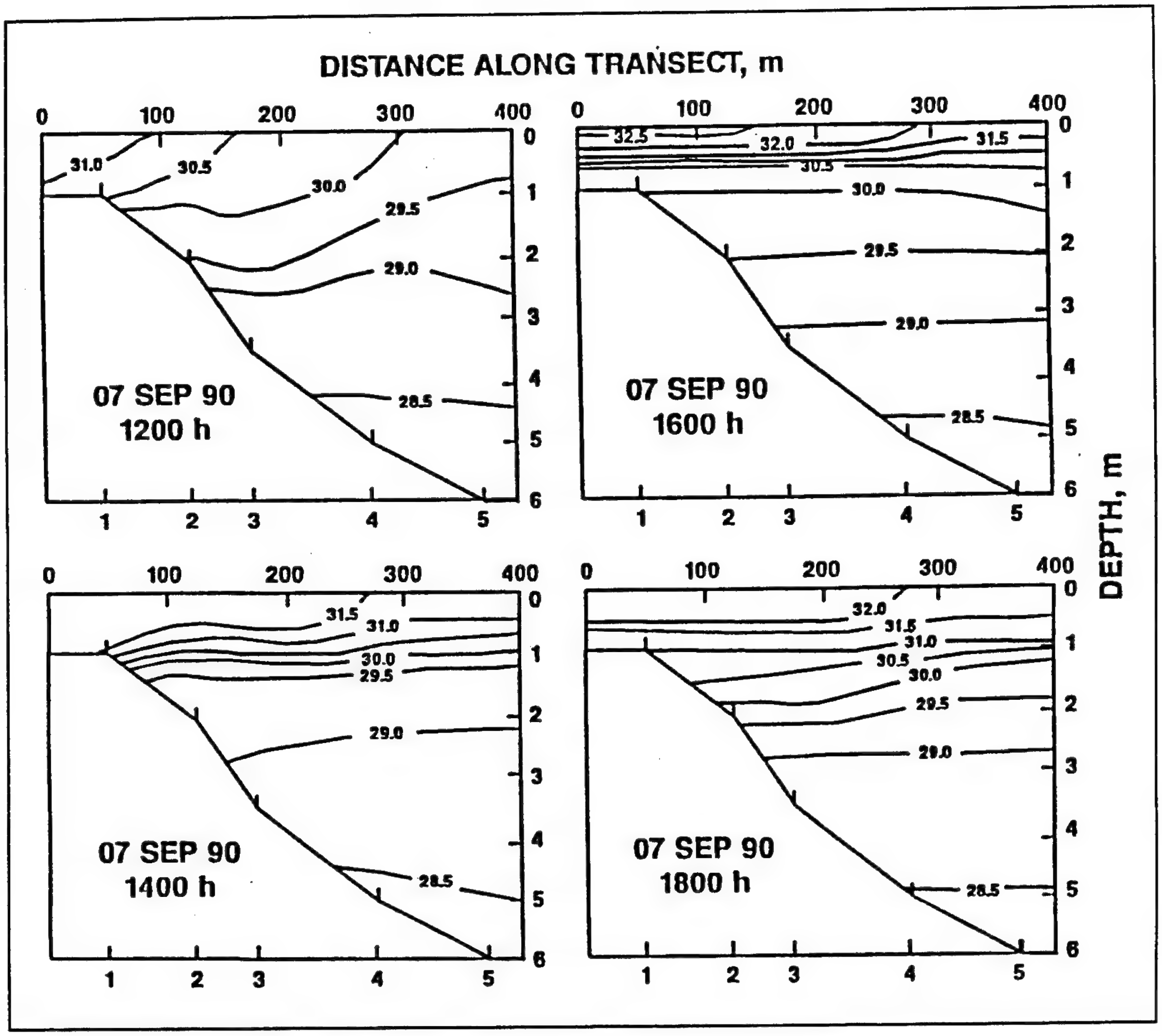

Figure 14. Longitudinal and vertical variations in water temperature (°C) at 1200, 1400, 1600, and 1800 hr on 07 September 1990

midafternoon (Figure 17), suggesting return flows of cooler water during convective water exchange.

Pattern 3 (Table 1) exhibited a high mean surface mixed layer; however, horizontal water temperature gradients were generally much lower in the early afternoon, suggesting minimal potential for convective exchange. This pattern, observed on 26 percent of the days in September, usually occurred during cooling trends with net heat loss from the water column (Figure 10b), which may explain the lack of strong horizontal water temperature gradients and development of convective exchanges. Pattern 4, exemplified by thermal patterns occurring on 01 September, exhibited the greatest mean surface mixed layer, highest mean wind speed, and intermediate horizontal water temperature gradients. These patterns, resulting in apparent convective exchange with a vertically expansive overflow, occurred on only two afternoons in September (Figure 17).

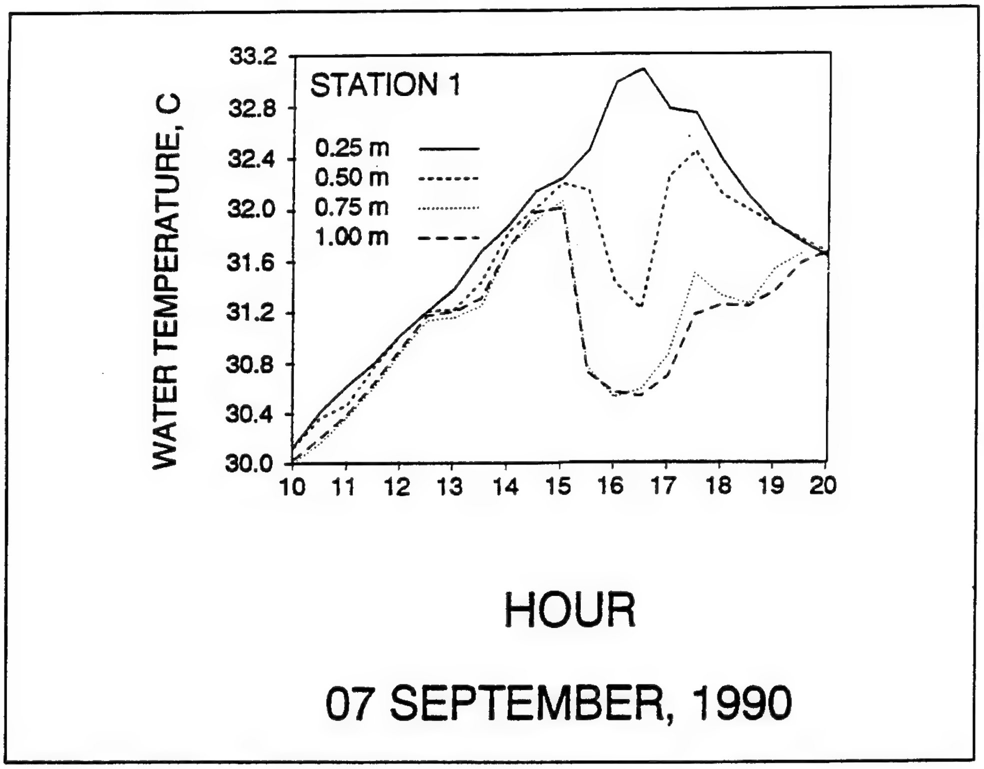

Figure 15. Variations in water temperature at Station 1 between 1000 and 2000 hr on 07 September 1990

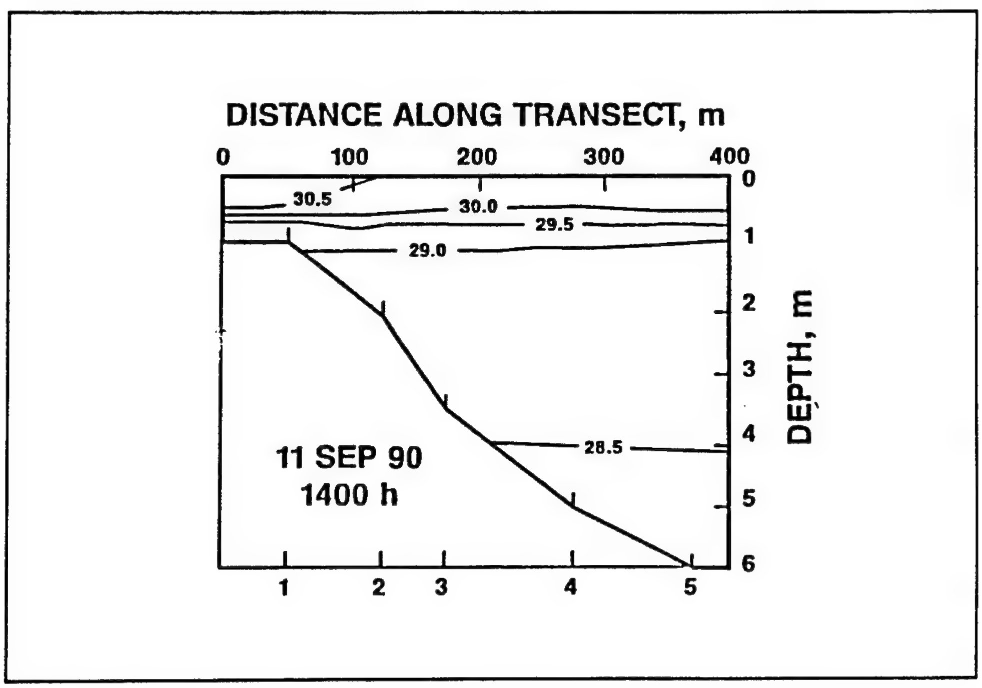

Figure 16. Longitudinal and vertical variations in water temperature (°C) at 1400 hr on 11 September 1990

Table 1
Cluster Analysis of Relationships Among Mean Surface Mixed Layer Depth, Mean Wind Speed, and Mean Horizontal Water Temperature Gradient During Periods of Differential Heating, September 1990

Cluster Number	Frequency of Occurrence	Surface Mixed Layer, m	Wind Speed m/sec	Temperature Gradient, °C
1	8	0.73 (10)	1.7 (0.7)	0.32 (0.30)
2	7	1.14 (12)	2.2 (0.7)	0.63 (0.21)
3	6	1.71 (10)	2.6 (1.0)	0.19 (0.08)
4	2	≥2.00 (0)	5.3 (3.6)	0.37 (0.07)

Note: Means were determined for the time period 1200-1400 hr (n = 5) over a duration of 23 days. Standard deviations are shown in parentheses.

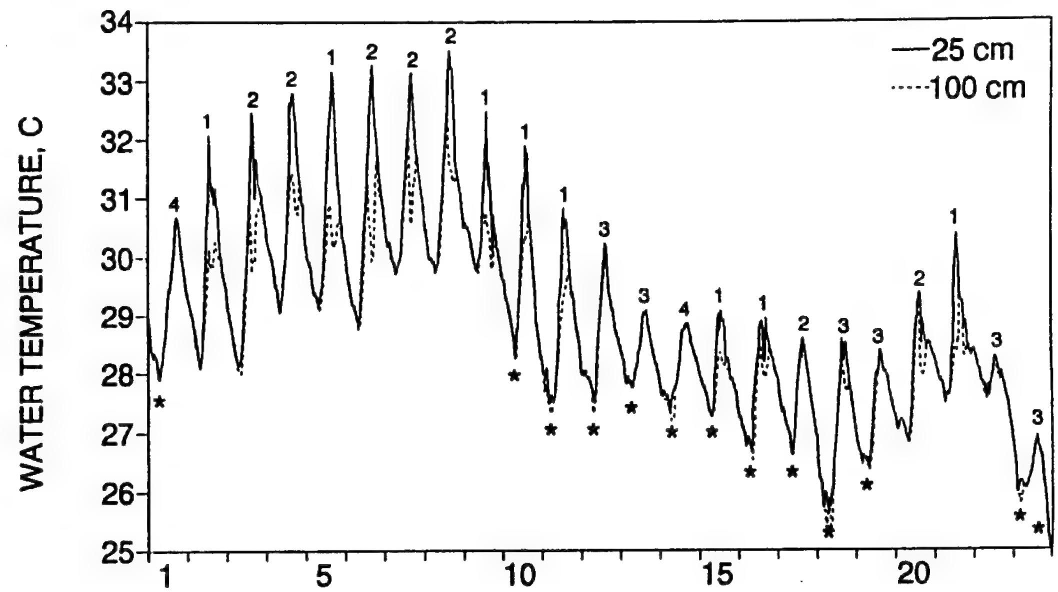

Figure 17. Diel variations in water temperature at Station 1 from 01 to 23 September 1990 (Numbers above water temperatures at 25-cm depth identify cluster category during periods of differential heating (see Table 1). Patterns 1, 2, and 4 coincided with periods of probable convective exchanges (see text). Asterisks below water temperatures denote exchanges during periods of differential cooling)

Discussion

During differential heating, wind appears to be very important in influencing conditions for hydraulic transport by regulating the depth of the surface mixed layer, and thus, the distribution of heat in the water column. Periods of relatively strong daytime heating in conjunction with wind-generated mixing appear to result in the distribution of heat to deeper depths, thereby promoting the development of a vertically expansive overflow during convective exchange. With little wind-generated mixing, surface water heating is very shallow (on the order of a few centimeters) during differential heating phases in the Minky Creek embayment. Thus, convective water exchanges are probably taking place in a very thin surface layer under these conditions.

Based on variations in water temperature contours, the potential for convective exchanges during differential cooling and heating occurred on 54 and 74 percent of the days, respectively, during September. In general, it appeared that conditions for exchanges during differential cooling predominated only when the water column exhibited a net daily heat loss. During periods of net daily heat gain in the water column, in contrast, convective exchanges occurred primarily as a result of differential heating. Strong nighttime differential cooling followed by strong daytime differential heating during periods of net daily heat gain in the water column in September was rarely detected. These results suggest, overall, that convective exchange patterns may be regulated, in part, by weather patterns that result in general warming and cooling trends. More detailed information is needed over an entire season to better understand the affects of weather trends on long-term patterns of convective water exchange.

Variations in the occurrence of differential cooling versus heating during the month of September and their potential impact on hydraulic transport characteristics (i.e., overflows or underflows) have important implications for the exchange of nutrients between littoral and pelagic zones and availability to phytoplankton communities located in the euphotic zone (James and Barko 1991a,b). They may also play an important role in regulating the residence time and fate of aquatic herbicides. In particular, macrophytes contain a considerable amount of tissue phosphorus and other nutrients that can become a major source of soluble nutrients to the water column during leaching and decay (Barko and Smart 1980; Carpenter 1980; Landers 1982) after a herbicide treatment. Movement of these soluble nutrients via convective exchanges as underflows during the night and overflows during the day may result in considerable nutrient redistribution and potential availability to phytoplankton communities. In addition, herbicide application strategies must consider the potential for movement of herbicides from target areas, as a result of both convective exchanges and wind-generated exchanges. Stefan, Horsch, and Barko (1989) and Monismith, Imberger, and Morison (1990) have suggested that the residence time of shallow regions can be on the order of hours, as a result of convective exchanges. These short residence times need to be considered when evaluating interactions between herbicide concentration and exposure times (Fox et al. 1991; Netherland, Green, and Getsinger 1991;

Netherland and Getsinger 1992) for macrophyte control. They may also result in the movement of herbicides to undesirable locations, such as the open water.

4 Thermal Patterns and Convective Circulation in the Minky Creek Embayment of Guntersville Reservoir During 1991[1]

Introduction

During 1990 and 1991, differential heating, cooling, and resultant convective circulation patterns were examined in an embayment (Minky Creek) of Guntersville Reservoir, Alabama. Vertical and horizontal variations in water temperature were used to examine differential heating and cooling in the reservoir. Objectives were to identify temperature patterns likely to produce convective circulation in this embayment and to document the frequency of their occurrence. Preliminary results from 1990 were summarized previously (James 1991). This report describes results of more extensive studies conducted in 1991.

Materials and Methods

Study site

Guntersville Reservoir, located on the Tennessee River in northeastern Alabama, is a hydropower and flood control impoundment operated by the Tennessee Valley Authority. The Minky Creek embayment of the reservoir (Figure 18) is relatively shallow (maximum depth of approximately 6 m), with an extensive littoral zone. Prior to 1990, the shallows were dominated by the submersed macrophyte *Myriophyllum spicatum*. Macrophyte biomass declined during 1990 in the Minky Creek embayment, as well as in other regions of the

1 Chapter 4 was written by Craig S. Smith, William F. James, and John W. Barko.

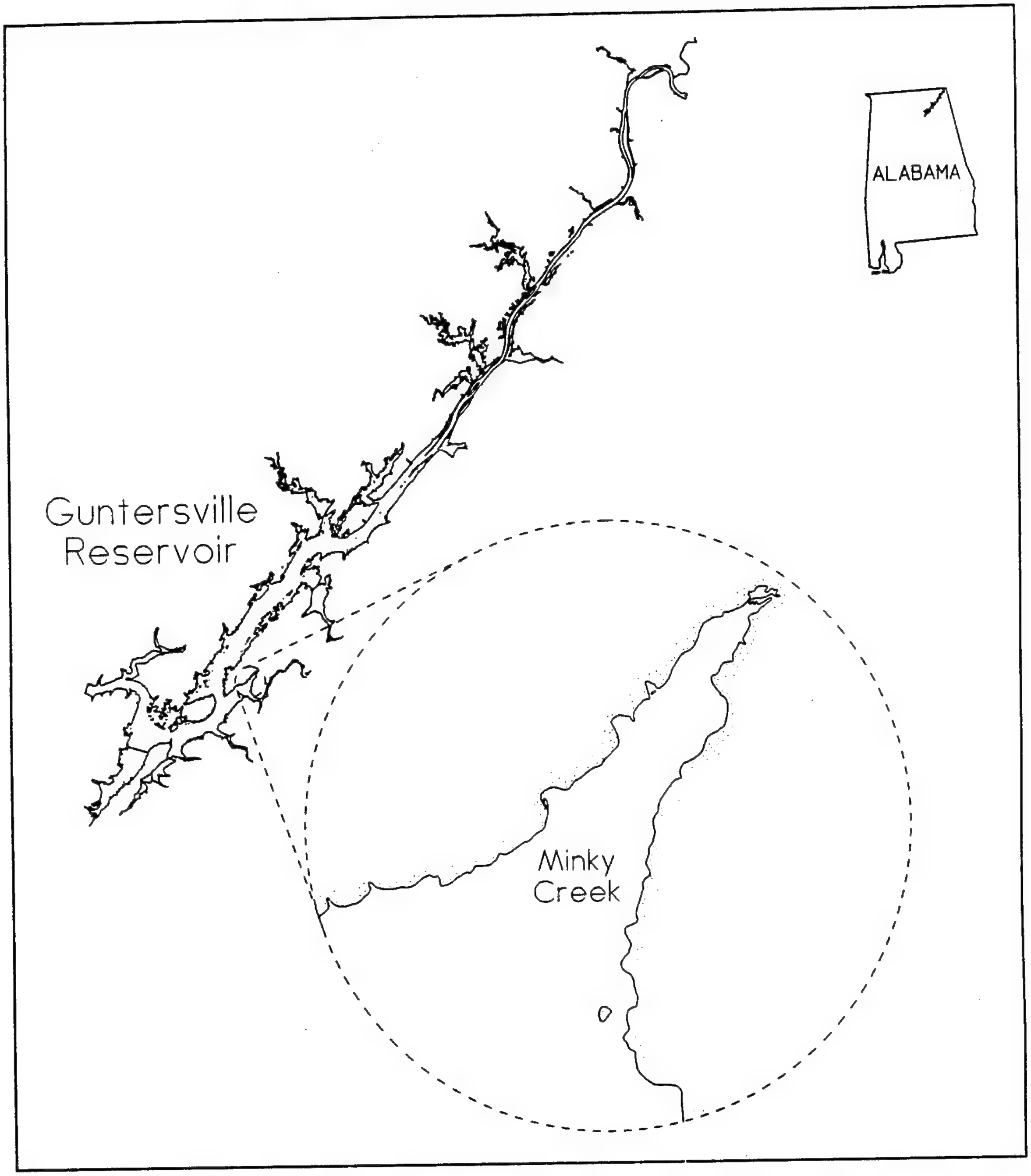

Figure 18. Location of Guntersville Reservoir and the Minky Creek Embayment

reservoir, and the embayment was essentially devoid of submersed vegetation throughout this study.

Temperature and weather stations

In 1991, water temperatures were measured along two transects (Figure 19). A lateral transect extended approximately 400 m out from the northern shore

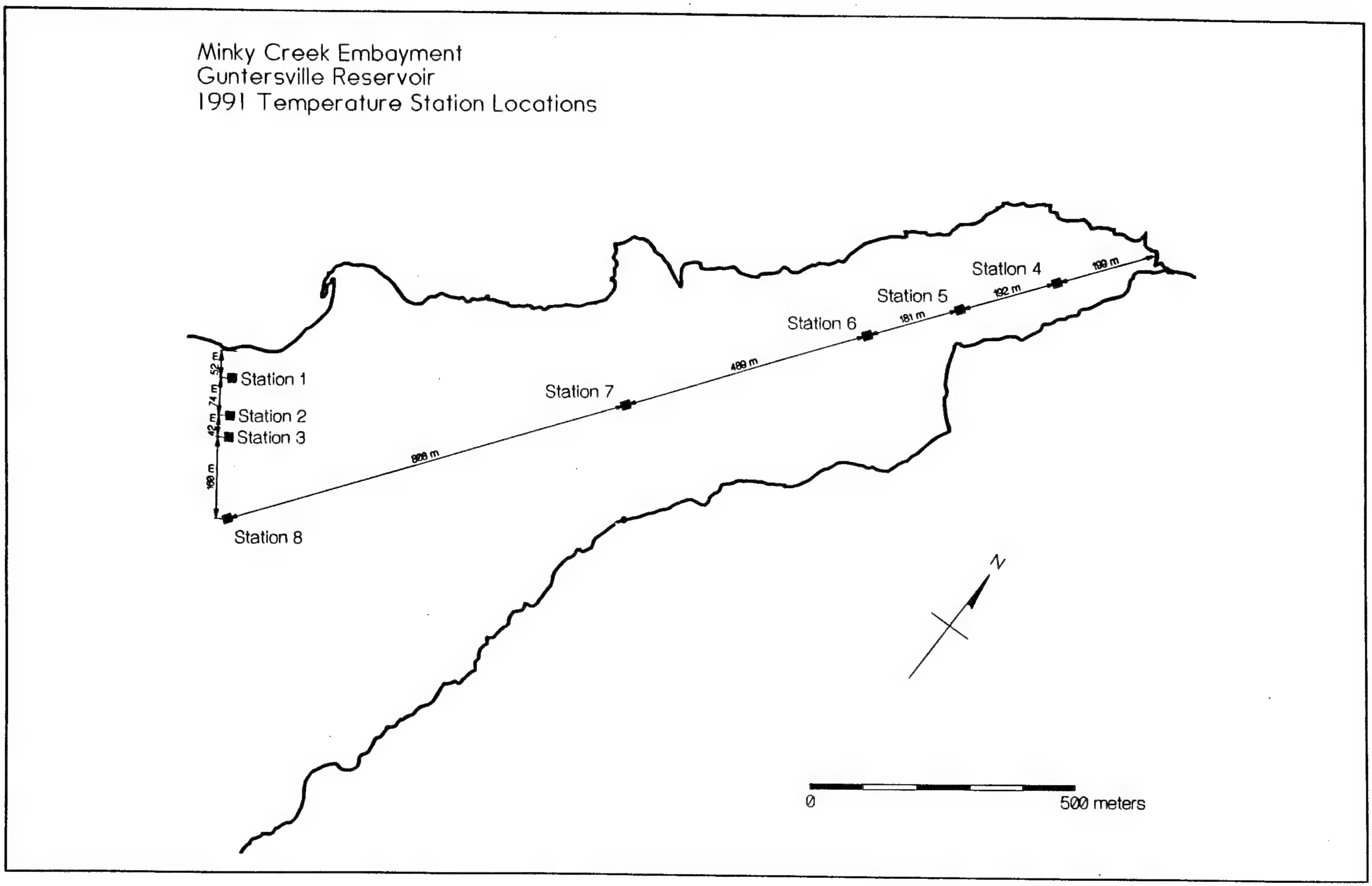

Figure 19. Locations of temperature monitoring stations during 1991

of the embayment. Stations for water temperature monitoring were located at the 1.0- (50 m from shore), 2.0- (125 m from shore), 3.5- (175 m from shore), 5.0- (275 m from shore), and 5.75-m (375 m from shore) depths on this transect. A second transect extended along the central axis of the embayment to the outermost station on the lateral transect, 1900 m from the head of the bay. Four additional temperature stations were arrayed along the central axis at depths of 0.8, 1.5, 2.2, and 3.8 m, corresponding to distances of approximately 200, 400, 600, and 1,100 m from shore, respectively. Recording temperature monitors (Omnidata International) were placed on permanently positioned platforms at all stations. Instantaneous water temperatures were measured every half hour at all stations with thermistor probes precalibrated to the nearest 0.01 °C. Thermistor probes were positioned at 0.25-m depth increments from 0.25 m to the bottom in locations less than 3.0 m deep. In deeper locations, thermistors were located at a depth of 0.25 m and at 0.50-m depth increments from 0.5 m to the bottom. Half-hour averages of wind speed and direction measurements made every 2 min were recorded at the outermost station (Station 8) and the one nearest the head of the embayment (Station 4). Instantaneous measurements of air temperature, relative humidity, and solar irradiance were recorded every 30 min at Station 6.

Analysis of temperature data

This report focuses primarily on the development of temperature patterns along the central axis of the embayment (Stations 4 through 8). Isotherms were drawn from water temperature observations by kriging, using the commercial software package Surfer. In determinations of vertical stratification, the daily mixed layer was considered to extend from the surface to the first thermal stratum having a temperature gradient of 1°C/m or greater. The depth of the mixed layer each day was determined at 1600 hr, when daytime thermal stratification is typically maximal. Near-surface horizontal temperature gradients along the central axis of the embayment were calculated as the difference between temperatures measured at the 0.25-m depth at Stations 8 and 5. The innermost station (4) was not used for comparisons because of malfunctions in the 0.25-m temperature sensor.

Patterns of thermal stratification along the main axis of the embayment during 1991 were compared using cluster analysis. Water temperature observations at each time interval were first normalized by expressing each as a difference from the deepest measurement at the station furthest offshore (i.e., 5.0-m depth at Station 8). Normalization highlighted relative differences between locations and eliminated overall seasonal temperature trends. Normalized water temperature observations were then analyzed using the procedure FASTCLUS in SAS (SAS Institute, Inc. 1988). The maximum number of clusters was arbitrarily set at 6. FASTCLUS ignores observations with missing values in constructing clusters, but assigns such observations to clusters, where possible.

Dye injection studies

On 16 October 1991, water movements were traced by injecting dye and following its movement. Prior to the injection of dye, 34 marker buoys were placed along the main axis of the embayment at 25-m intervals from Station 4 to Station 7. The study commenced with the injection of dye at 0800 hr. A mixture of 4.2 ℓ Rhodamine WT and 4.2 ℓ of methanol was diluted with approximately 7 ℓ of lakewater for injection. The injection area was 20 by 4 by 1 m deep and was located 30 m from Station 5 between Stations 5 and 6. Dye was injected at 0.0-, 0.5-, and 1.0-m depths in order to distribute dye vertically throughout the water column. The dye mixture was injected by pumping it through a herbicide-injection manifold about 2 m in length at a rate of 0.07 ℓ/sec while the boat moved back and forth through the injection zone (two injections sweeps at each depth). The injection took approximately 20 min to complete.

Dye movement was tracked by measuring dye concentrations with a fluorometer. Concentration measurements were made at 0.25-m-depth intervals at marker buoy locations along the central transect and at other arbitrary locations to either side of the transect. Positions of sampling stations off the central transect were approximated by estimating the distance and direction to the nearest marker buoys. The distribution of dye at the surface was also estimated visually and traced onto a map of the embayment. Sampling began within 1 hr of injection and continued until 1530 hr.

Results

Meteorological conditions at the site

Excluding diel variation, air and water surface temperatures were relatively stable from early June until mid-September of 1991 (Figure 20). A general downward trend in air and water temperatures began in mid-September and continued until the end of the study in mid-November. Short-term warming and cooling trends, each lasting a few days, were frequent throughout both the stable and declining periods.

Daily average wind velocities and directions at the outermost station (Station 8) during May through November 1991 are shown in Figure 21. Daily average wind velocities during this period ranged from 0.8 to 4.7 m/sec. Average wind direction was highly variable. Winds rarely originated in the quadrant from northwest to northeast; those that did were never strong. During the spring and summer, winds were frequently from the southeast. Winds from the NW to WNW were uncommon during the summer, but increased in September and October, and became predominant in November.

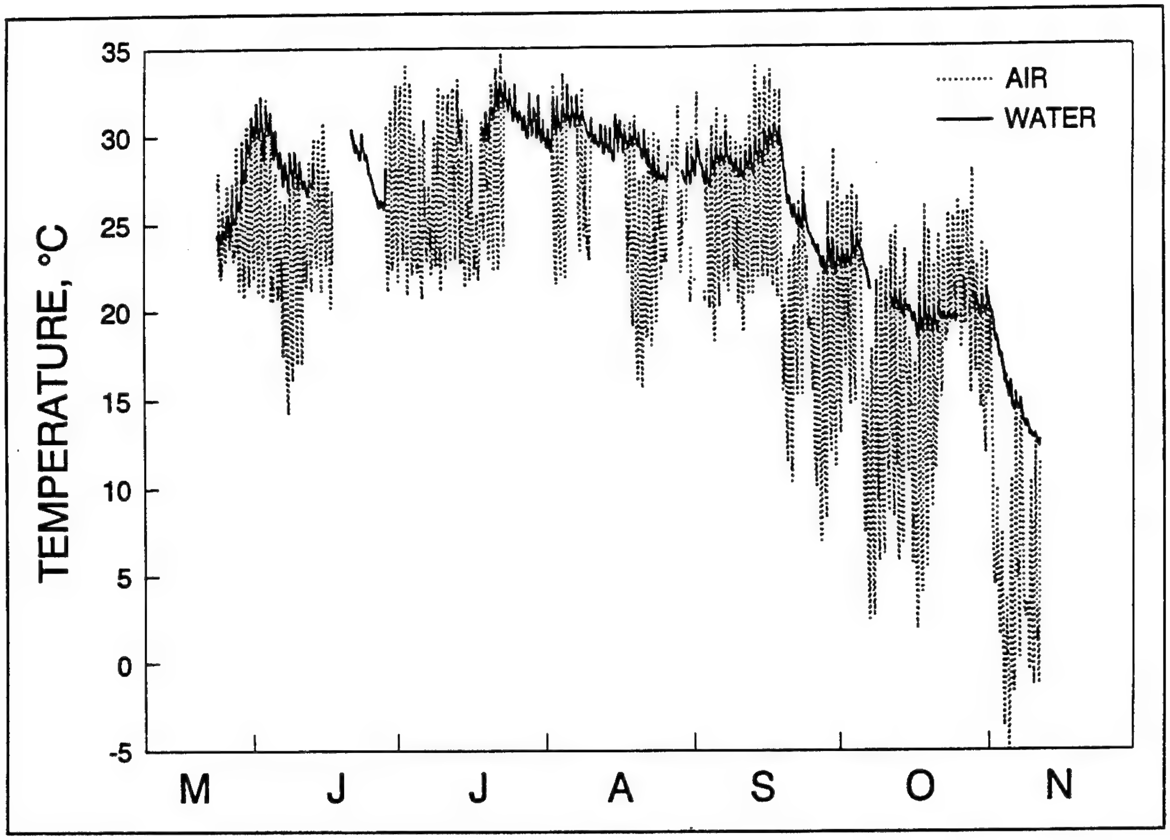

Figure 20. Hourly air and water surface (at the outermost station) temperatures during 1991

Water temperatures

Examples of the temperature changes produced by differential heating and cooling are shown in Figures 22 through 28. Each of these figures illustrates isotherms drawn every 4 hr for a randomly selected 24-hr period, one from each month during which temperature measurements were taken during 1991.

From May 29-30, there was considerable differential heating of the shallows during the daytime and only very limited nighttime cooling (Figure 22). These dates fell in the middle of an overall warming period, which lasted several days. Surface water temperatures along the central axis of the embayment increased by 1 to 2 °C from the beginning of the period until the end. While the water throughout most of the embayment was still warming up, there was very strong vertical stratification at the deeper stations (>2.0 m deep). The two shallowest stations (<1.5 m deep) were unstratified in the morning (0800 hr) and stratified only briefly (1200 hr) before daytime heating warmed the entire shallows (1600 and 2000 hr).

June 7-8 occurred during a cooling period, as there was considerable nighttime cooling but little differential heating (Figure 23). For the morning of

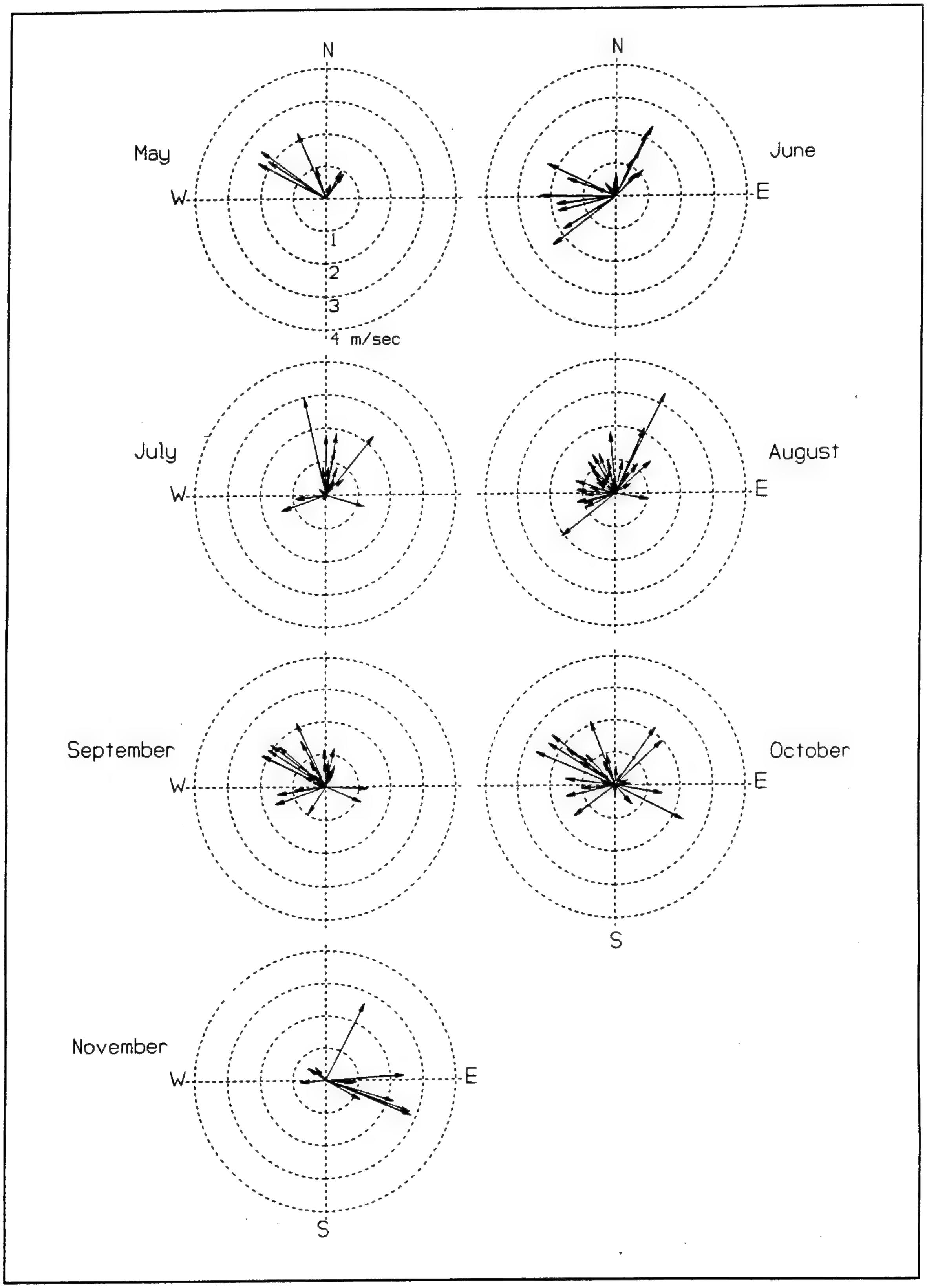

Figure 21. Distribution of daily average wind direction and velocity, 1991 (Arrows point in direction of air movement (i.e., away from source of the wind), and arrow length is proportional to daily average wind velocity)

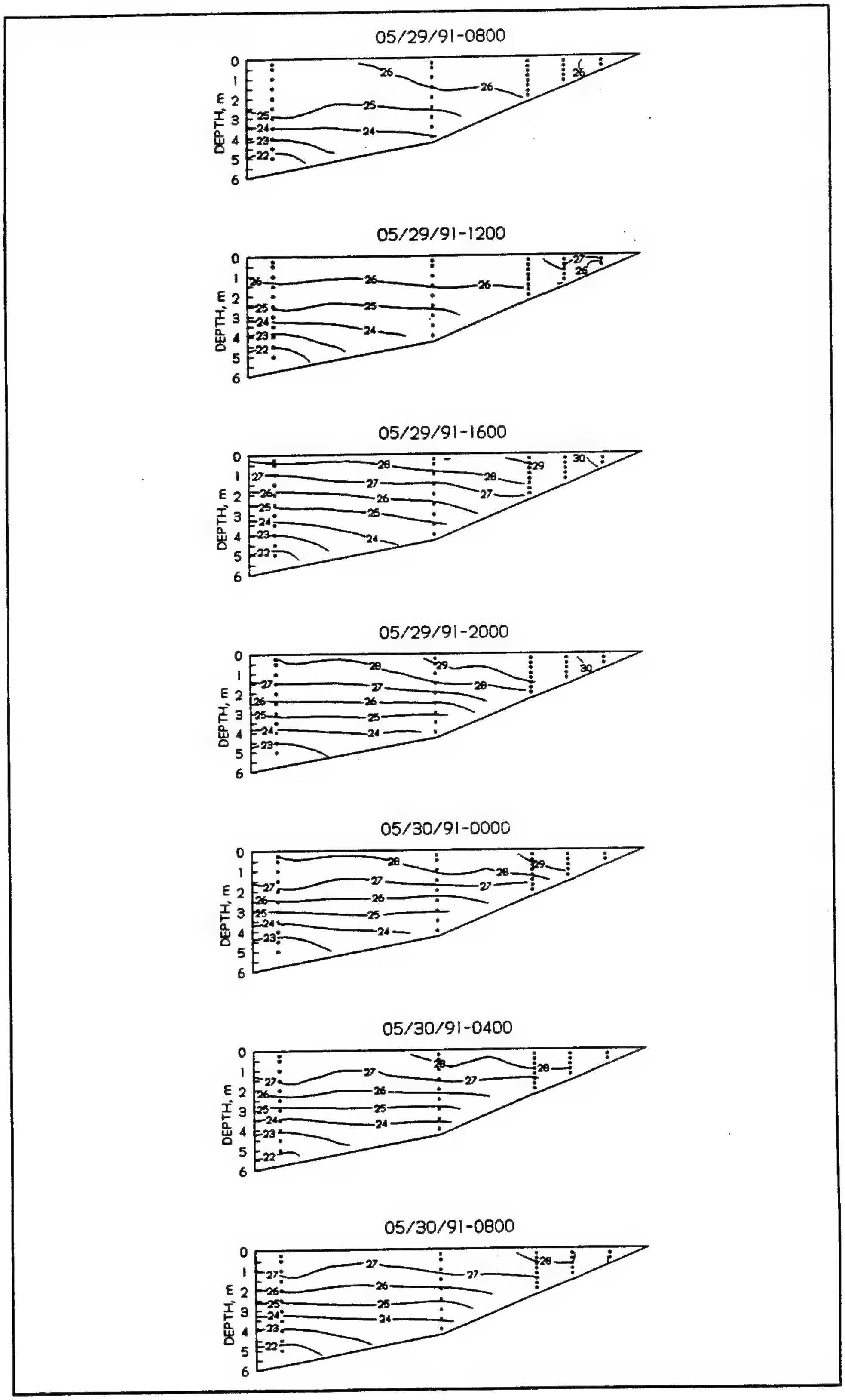

Figure 22. Temperature patterns along central transect at 4-hr intervals on May 29 and 30, 1991 (Asterisks show locations of temperature sensors)

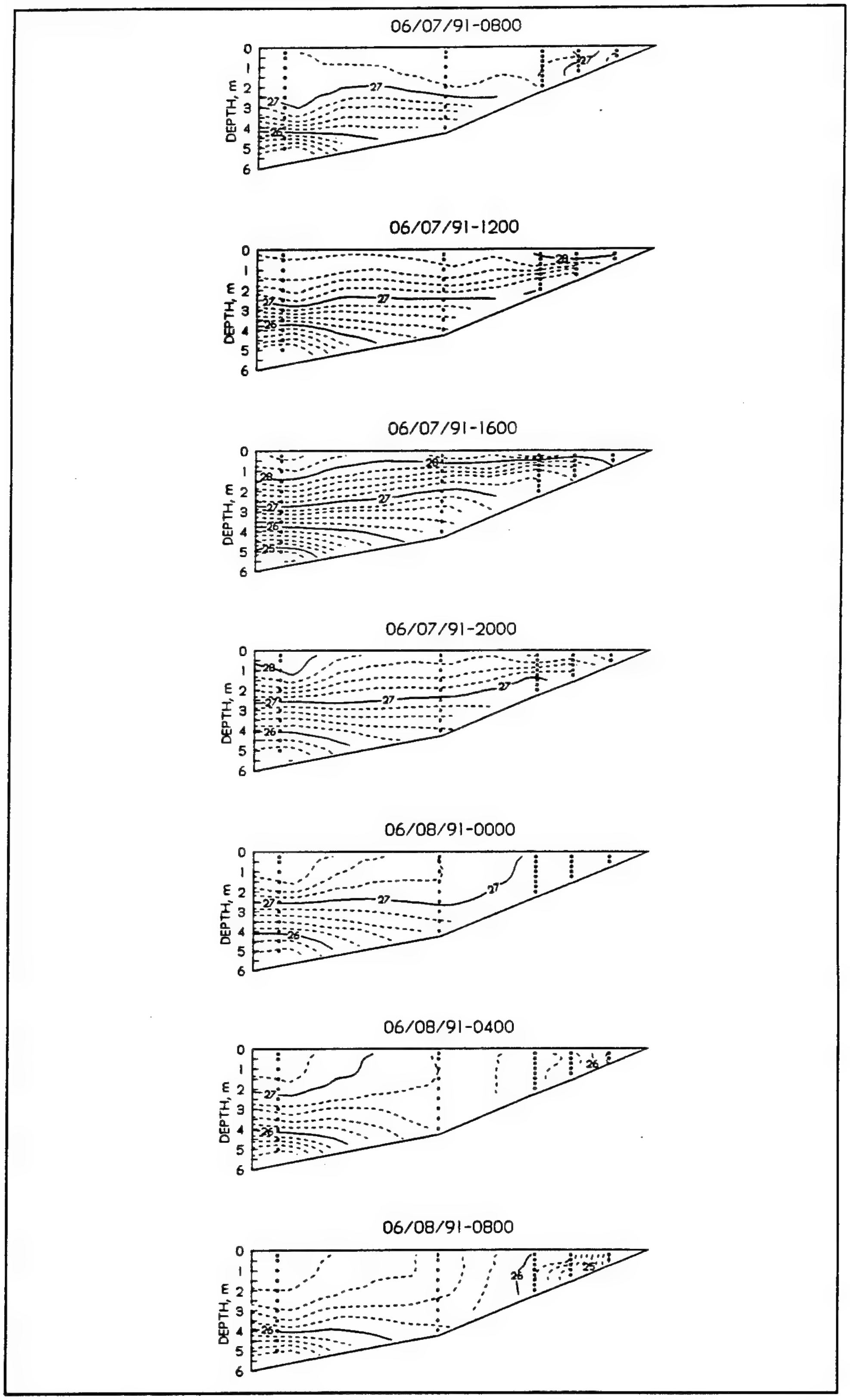

Figure 23. Temperature patterns along central transect at 4-hr intervals on June 7 and 8, 1991 (Asterisks show locations of temperature sensors)

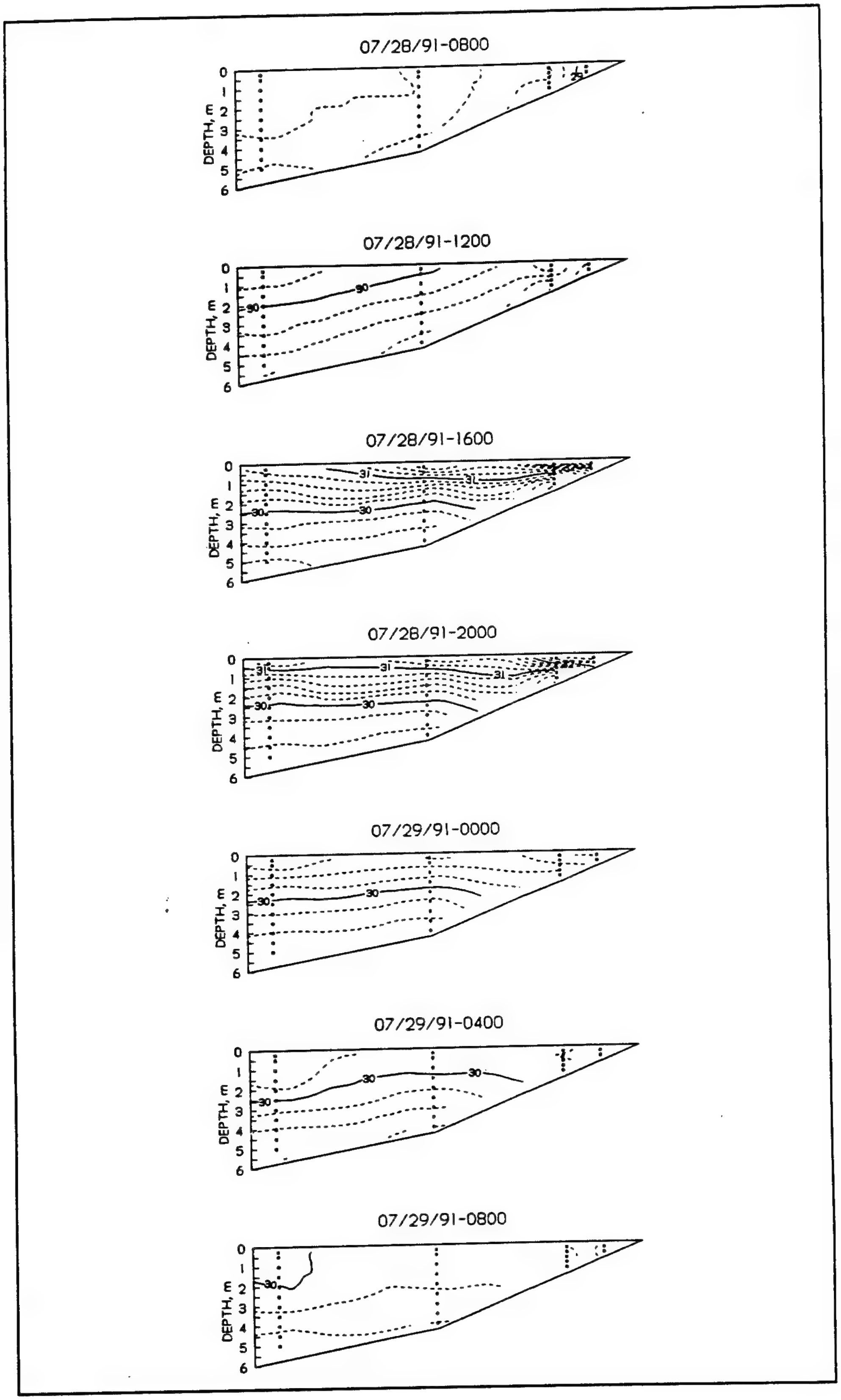

Figure 24. Temperature patterns along central transect at 4-hr intervals on July 28 and 29, 1991 (Asterisks show locations of temperature sensors)

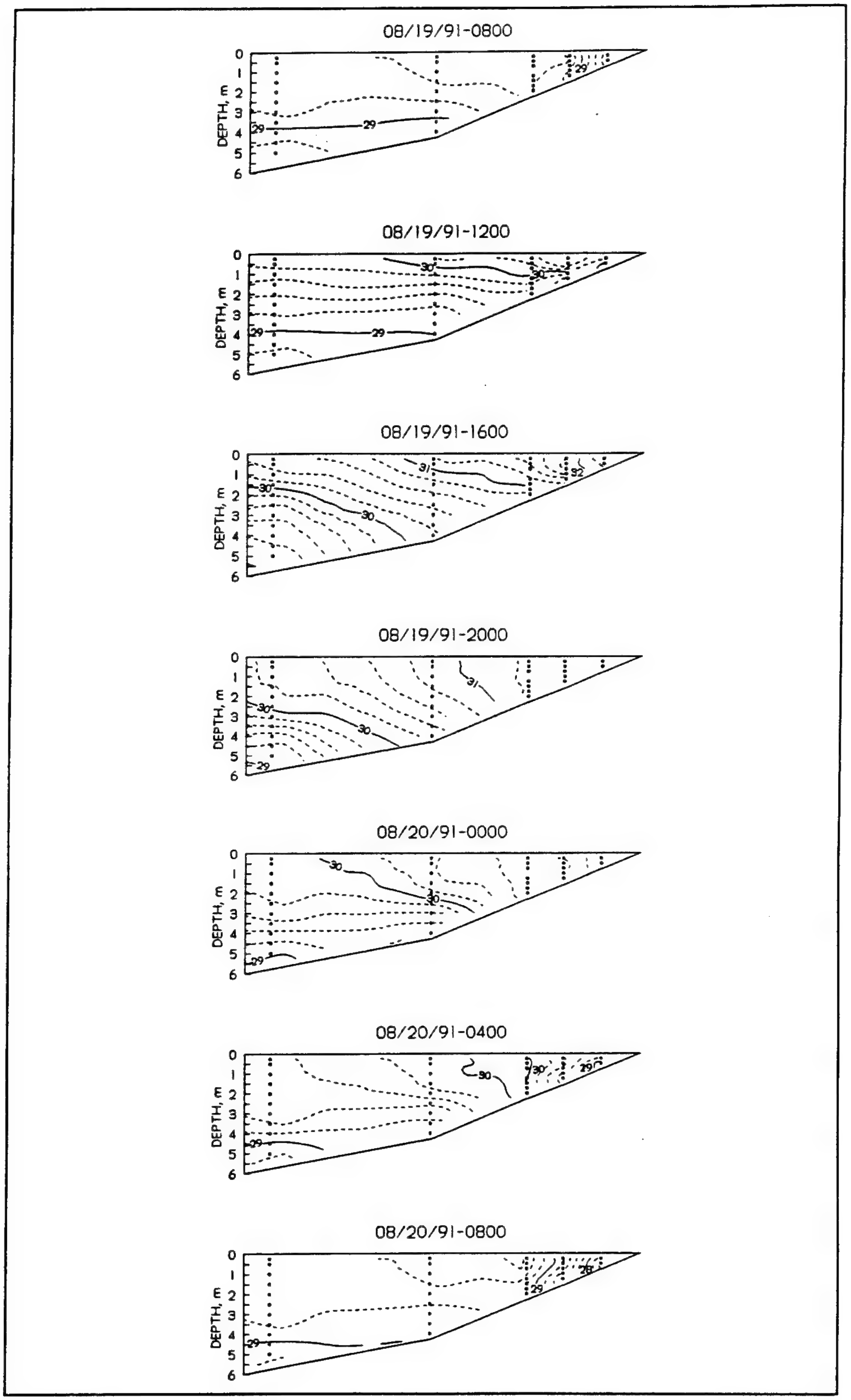

Figure 25. Temperature patterns along central transect at 4-hr intervals on August 19 and 20, 1991 (Asterisks show locations of temperature sensors)

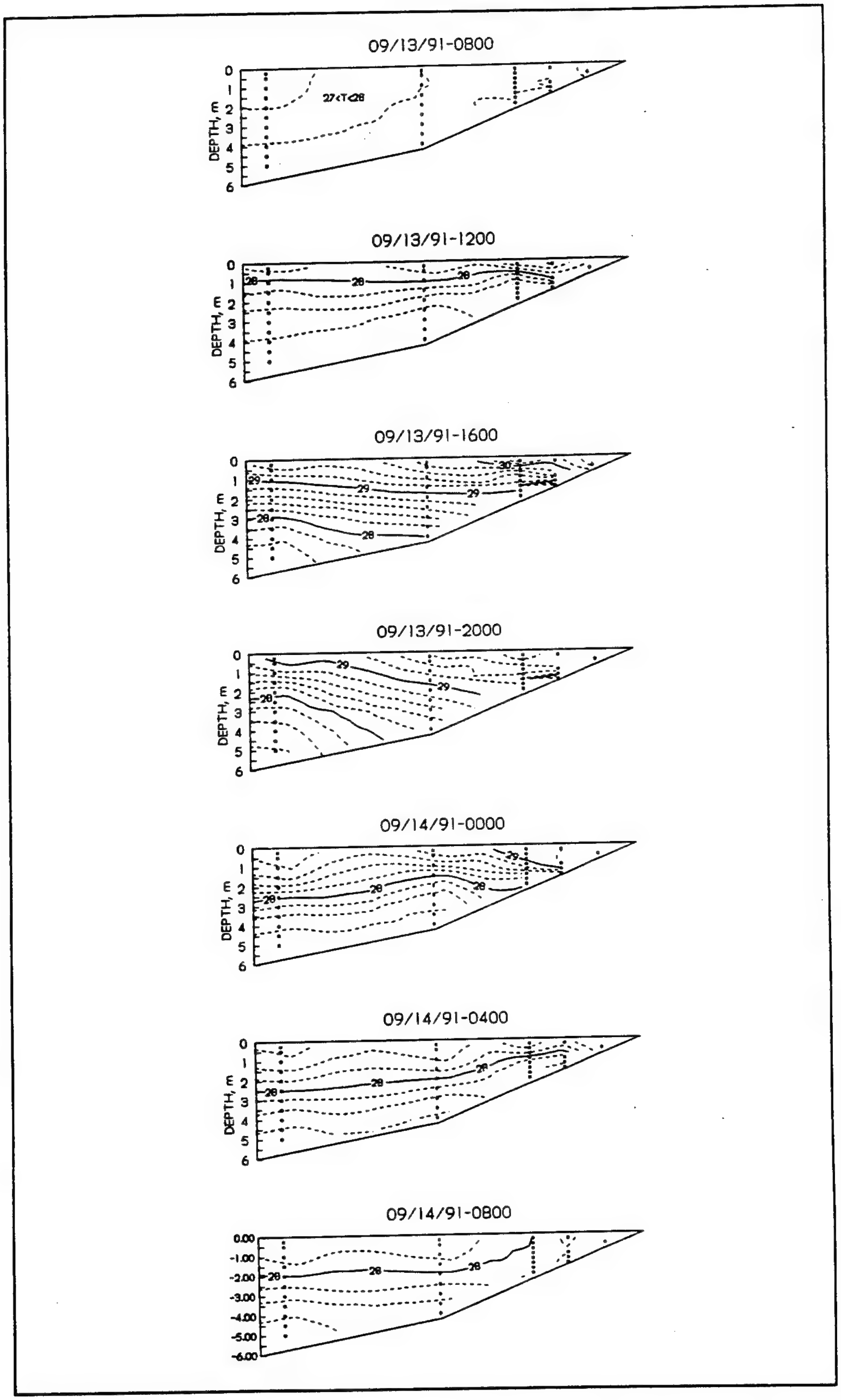

Figure 26. Temperature patterns along central transect at 4-hr intervals on September 13 and 14, 1991 (Asterisks show locations of temperature sensors)

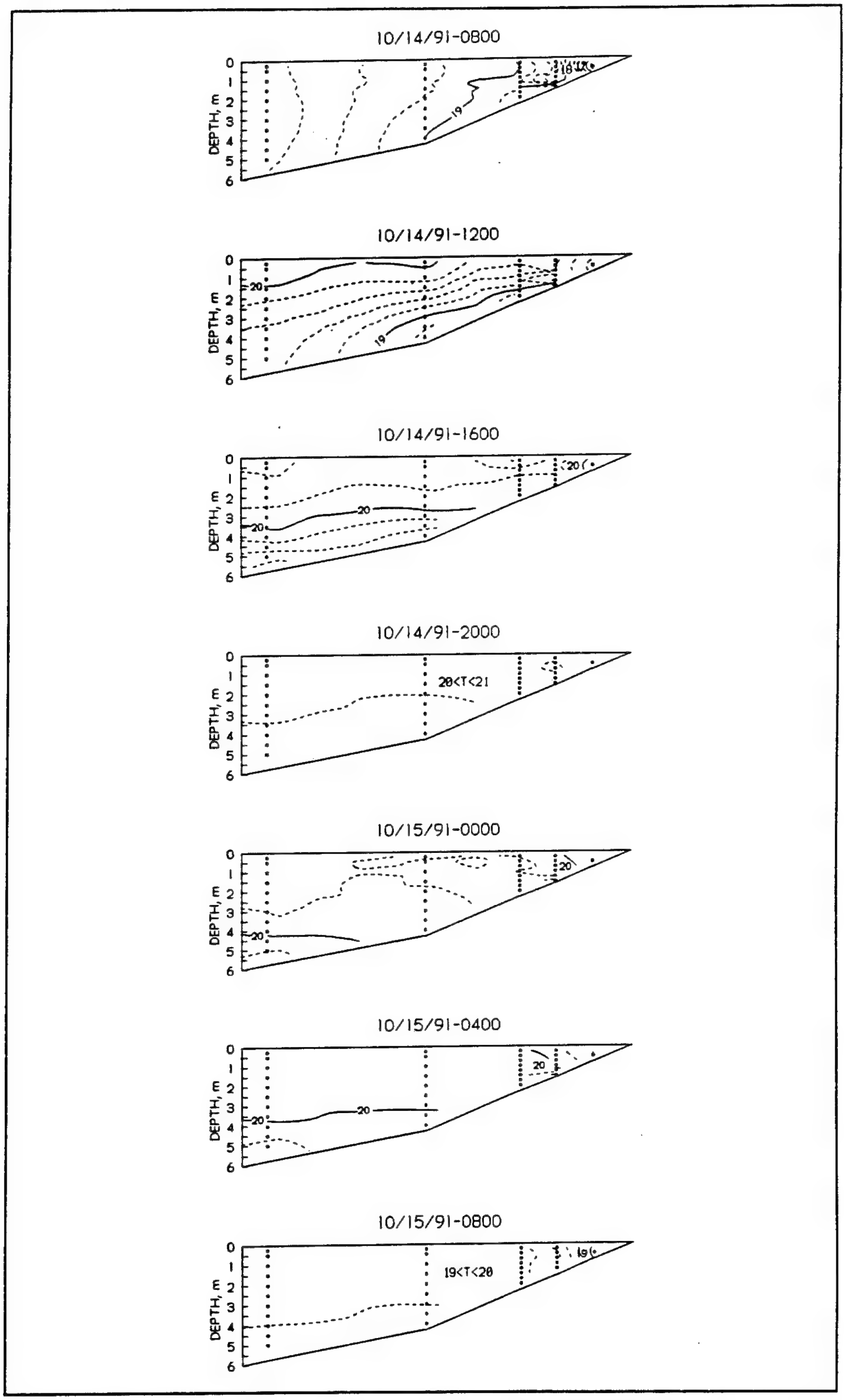

Figure 27. Temperature patterns along central transect at 4-hr intervals on October 14 and 15, 1991 (Asterisks show locations of temperature sensors)

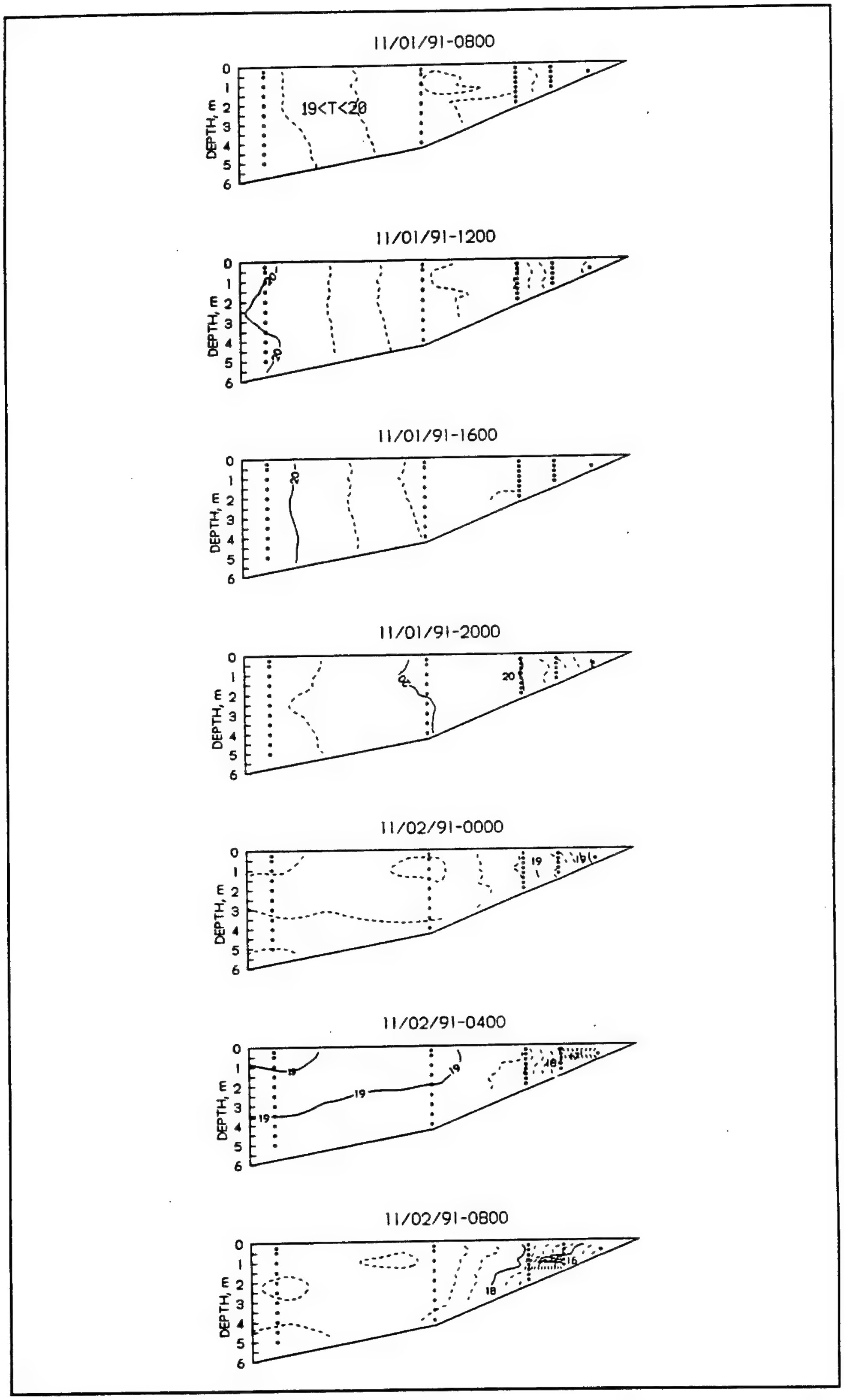

Figure 28. Temperature patterns along central transect at 4-hr intervals on November 1 and 2, 1991 (Asterisks show locations of temperature sensors)

June 7, isotherms show the characteristic pattern that indicates nighttime convective circulation, i.e., a mass of cool water moving downslope from the shallows. Daytime heating on June 7 resulted in the warming of only a shallow layer and was just sufficient to produce uniform surface temperatures along the transect by 1600 hr. By late afternoon (1600 hr), all traces of a horizontal temperature gradient disappeared. Nighttime cooling was substantial and left surface temperatures 1 to 2 °C cooler at the end of this period than at the beginning. By 0800 hr, cool water extended out past Station 6, but there was little evidence of an underflow of cold water, probably because of vertical mixing caused by relatively strong winds (up to 14 m/sec) during the night.

Isotherms from July 28-29 illustrate temperature changes common during much of the summer (Figure 24). By this time of year, the entire embayment had warmed, and vertical stratification was short lived and confined to periods following heating or cooling. As on many dates, heating and cooling were substantial but comparable, and water temperatures at the end of the period were very similar to initial ones. At 0800 hr on July 28, temperatures in most of the embayment were between 29 and 30 °C. The shallowest station had cooled overnight and was slightly below 29 °C. By 1600 hr, daytime heating had produced strong vertical stratification in the upper 2.0 m of the water column. Surface temperatures at the two shallowest stations exceeded those elsewhere by up to 1 °C, but differential warming of the shallow was largely confined to the surface. Strong stratification persisted until 2000 hr, but dissipated overnight. By 0800 hr on July 29, the embayment was again nearly isothermal.

August 19-20 was another period during which strong heating and cooling were nearly balanced, producing little net temperature change (Figure 25). At 0800 hr on August 19, the area around the shallowest station and the bottom layers (below 3.0 m) at the outermost two stations were slightly below 29 °C, while other areas were slightly above 29 °C. Daytime heating was strongly differential, with warm temperatures extending much deeper at shallow stations than at deep ones. By 1600 hr, the shallowest station had been heated to temperatures above 32 °C to the bottom and temperatures at the second and third stations (5 and 6) exceeded 31 °C to a depth of approximately 1.5 m. By 0400 hr, nighttime cooling had dropped temperatures in the shallows below those in the center of the transect. By 0800 hr on August 20, the slant of isotherms between Stations 5 and 6 suggests an underflow of cooler water from the shallows. Final temperatures at the two shallowest stations were nearly 1 °C lower than at the beginning of the time period, but temperatures elsewhere changed little during the period.

During September 13-14, heating slightly exceeded cooling (Figure 26). At the start of the period, the embayment was nearly isothermal throughout. Strong daytime heating raised surface temperatures from below 28 to near 30 °C or slightly higher by 1600 hr. Surface temperatures at the shallowest stations were up to 1 °C warmer than that at the deepest station. Only the shallowest station was heated to a greater depth than other stations. By 0800 hr on September 14, cooling had destratified the three shallowest stations,

but the two deepest stations remained moderately stratified. Final temperatures were 0.5 to 1.0 °C warmer than initial ones, with the greatest changes occurring at the deeper stations.

October 14-15 illustrates warming following a period of very strong cooling (Figure 27). At 0800 hr on October 14, the shallowest station was nearly 3 °C cooler than the deepest station. Vertical stratification was absent from the ends of the transect but existed between Station 5 and 7, where isotherms suggest an underflow of cool water. Daytime heating led to development of vertical stratification at all but the shallowest stations by 1200 hr, and horizontal temperature gradients were nearly absent by 1600 hr. Cooling left the embayment nearly isothermal by 2000 hr. Most of the embayment remained isothermal through the end of the period, with slightly cooler water only at the two shallowest stations. Final temperatures were essentially unchanged at the deepest station, but were up to 2 °C warmer than initial temperatures at shallow stations.

November 1-2 was a period of very strong cooling (Figure 28). Final temperatures were 2 to 3 °C cooler than initial temperatures over the entire embayment. At 0800 hr on November 1, the embayment was nearly isothermal. Weak horizontal gradients were present, with the warmest water in the central part of the transect. The warm central area dissipated during the day, and there was no evidence of daytime heating. The shallows cooled dramatically during the night; by 0800 hr on November 2, temperatures there were more than 3 °C cooler than at the beginning of the period. Very cool water at Station 4 and on the bottom of Stations 5 and 6 suggests a considerable transport of cooler water along the bottom.

Analysis of water temperature patterns

Cluster analysis delineated six archetypical water temperature patterns, representing differing degrees of stratification resulting from varying histories of heating or cooling (Figure 29). Pattern 1 suggests strong differential cooling, as shown by the negative horizontal temperature gradient (i.e., cooler at shallow stations) and the underflow of cooler water at Stations 5, 6, and 7. Stratification increases with increasing pattern number. Intermediate numbered patterns (e.g., 2, 3, and 4) may result from either heating of lower numbered patterns or cooling of higher numbered ones. The two patterns showing the greatest stratification (5 and 6) occurred only after periods of surface heating in the spring and early summer (May through early July), when relatively cool water was present at the bottom of the deeper stations. Other patterns occurred throughout most of the period of measurement.

Daily heating and cooling were sufficient to produce marked alterations in temperature stratification within the embayment during most 24-hr periods. Eighty-seven percent of the 24-hr periods examined included observations that fell into two or more temperature stratification patterns (Table 2). Half of the dates when a single pattern persisted for 24 hr occurred in November, when

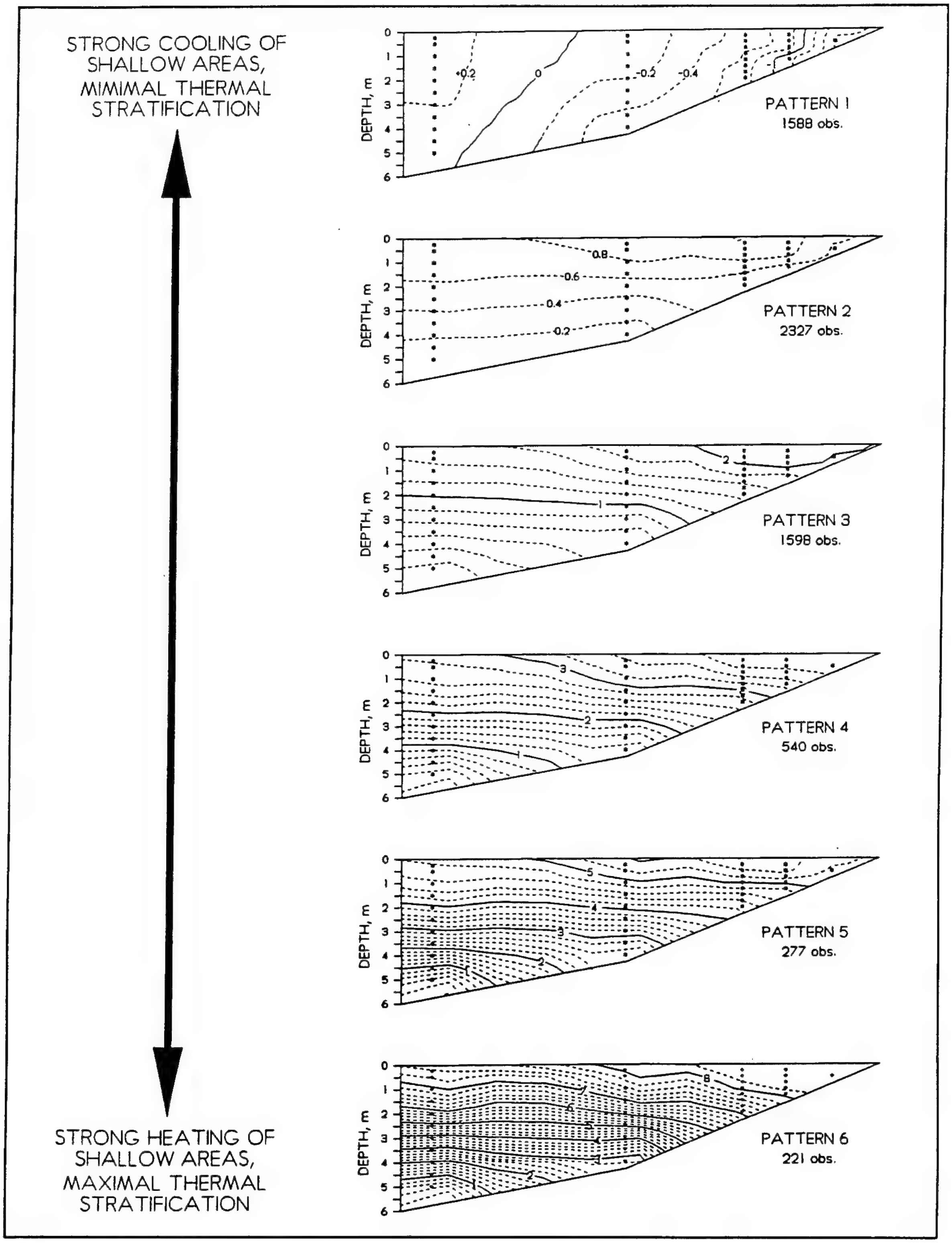

Figure 29. Temperature patterns along central transect during 1991 that represent final seeds of the six temperature clusters selected by FASTCLUS (Temperatures are indicated as deviations (in C°) from water temperature at 5.0-m depth of Station 8. Asterisks show locations of temperature sensors)

Table 2
Number of Temperature Patterns Occurring Daily (midnight to midnight) During 1991

Number of Patterns	Number of Days	Percent
1	17	13
2	77	57
3	40	29
4	1	1

the water column was cooling and often nearly isothermal. On most of these dates, temperatures fell into pattern 1.

Wind velocity affected the development of vertical temperature gradients. On calm, sunny days, steep vertical temperature gradients formed near the surface at all but the shallowest stations. Daytime vertical temperature gradients were typically greatest between 1330 and 1630 hr. The depth of the late afternoon (1600 hr) mixed layer increased with increasing wind velocity. On very calm days, the late afternoon mixed depth was sometimes only 0.25 m or less, while on windy days, deeper stations were mixed to the bottom. The depth of the mixed layer at the outermost station (Station 8) was more highly correlated with the average wind velocity over the 8 hr preceding the measurement (i.e., 0800-1600 hr) than with averages over shorter or longer periods (Figure 30). Theoretically, wind stress is approximately proportional to the square of wind velocity (Hutchinson 1957), but correlations between the daily mixed depth and the square of average wind velocity were weaker than those with average wind velocity. Development of the daily mixed layer occurred essentially independently each day, as shown by the very weak correlation with the mixed depth from the previous day ($r^2 = 0.131$, $N = 134$).

Horizontal temperature gradients were also influenced by wind velocity. As with vertical gradients, horizontal gradients were disrupted by strong winds. The daily maximum horizontal temperature difference at the surface (0.25-m depth) between Stations 5 and 8 was negatively correlated with wind velocity. The strongest correlation between the intensity of the gradient and wind ($r^2 = 0.244$, $N = 138$, $P < 0.01$) was with the average wind velocity on the previous day. Effects of past conditions were slow to dissipate, as shown by the relatively strong positive correlation ($r^2 = 0.409$, $N = 138$, $P < 0.01$) of the horizontal temperature difference with that from the previous day.

Effects of wind direction on the development of vertical and horizontal temperature gradients were generally nondetectable. Correlations between the mixed depth or the horizontal temperature gradient strength and the vector components of the wind along the transect and perpendicular to it were weak and generally not significant ($P \geq 0.05$).

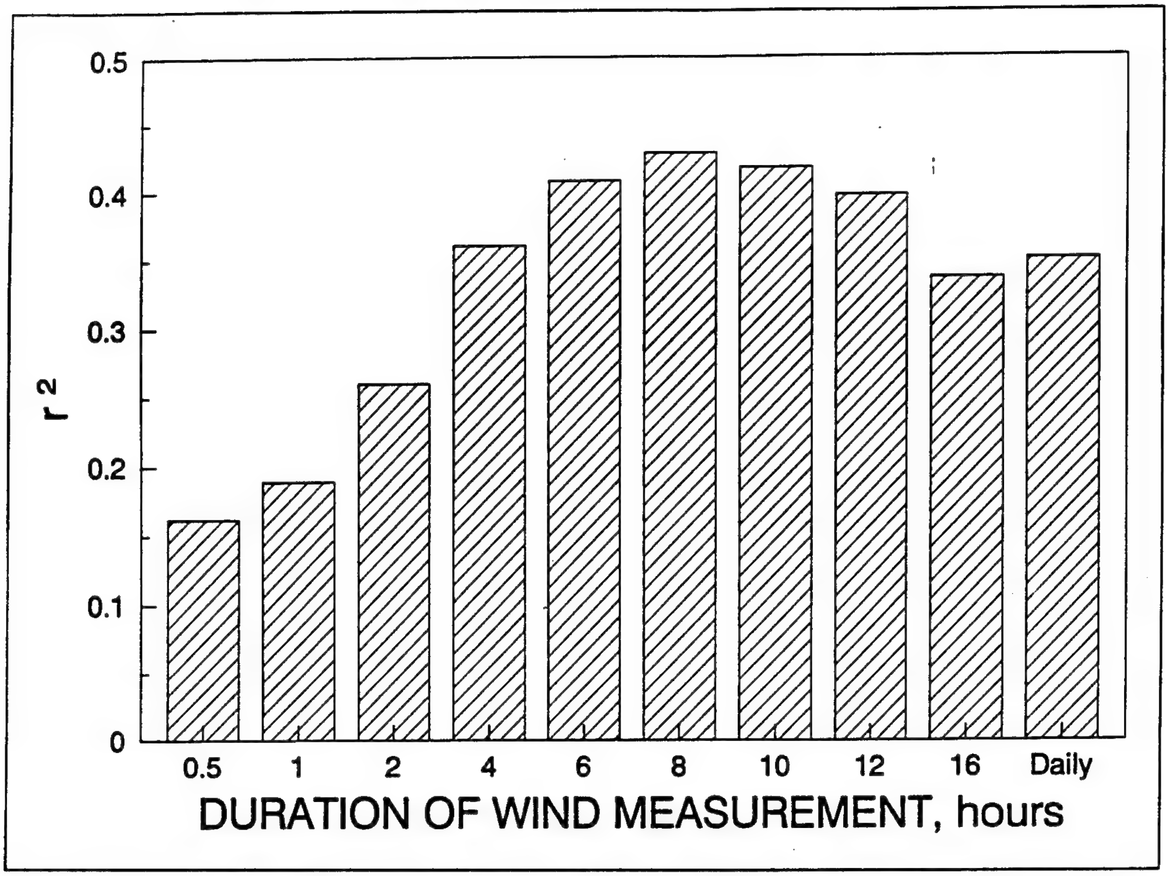

Figure 30. Strength of correlation between depth of late-afternoon (1600 hr) surface mixed layer and wind velocity, averaged over varying periods prior to 1600 hr

Dye movement

Temperatures measured during the night of October 15 and the morning of October 16 (Figure 31) indicate considerable nighttime cooling with an apparent underflow of cooler water at the central stations from 0800 through 1200 hr on October 16. Dye from the October 16 injection was initially distributed throughout the water column, with highest concentrations at 1.0- and 1.25-m depths. Movement of the dye cloud along the central transect (Figure 32) was towards shore in near-surface layers (from approximately 0 to 1.25 m) and away from shore in deeper layers (1.5 m and deeper). Average velocities of the dye cloud strata along the central transect, as measured by the movement of their centers of mass during the study, were 0.45 cm/sec at the surface and 0.63 cm/sec near the bottom. Winds during the study deflected surface water to and along the northwestern shore of the embayment (Figure 33). By the end of the study, a portion of the surface dye cloud had swept back across the central transect, where it appeared as a separate dye cloud near the surface at Station 6 and beyond (see Figure 32).

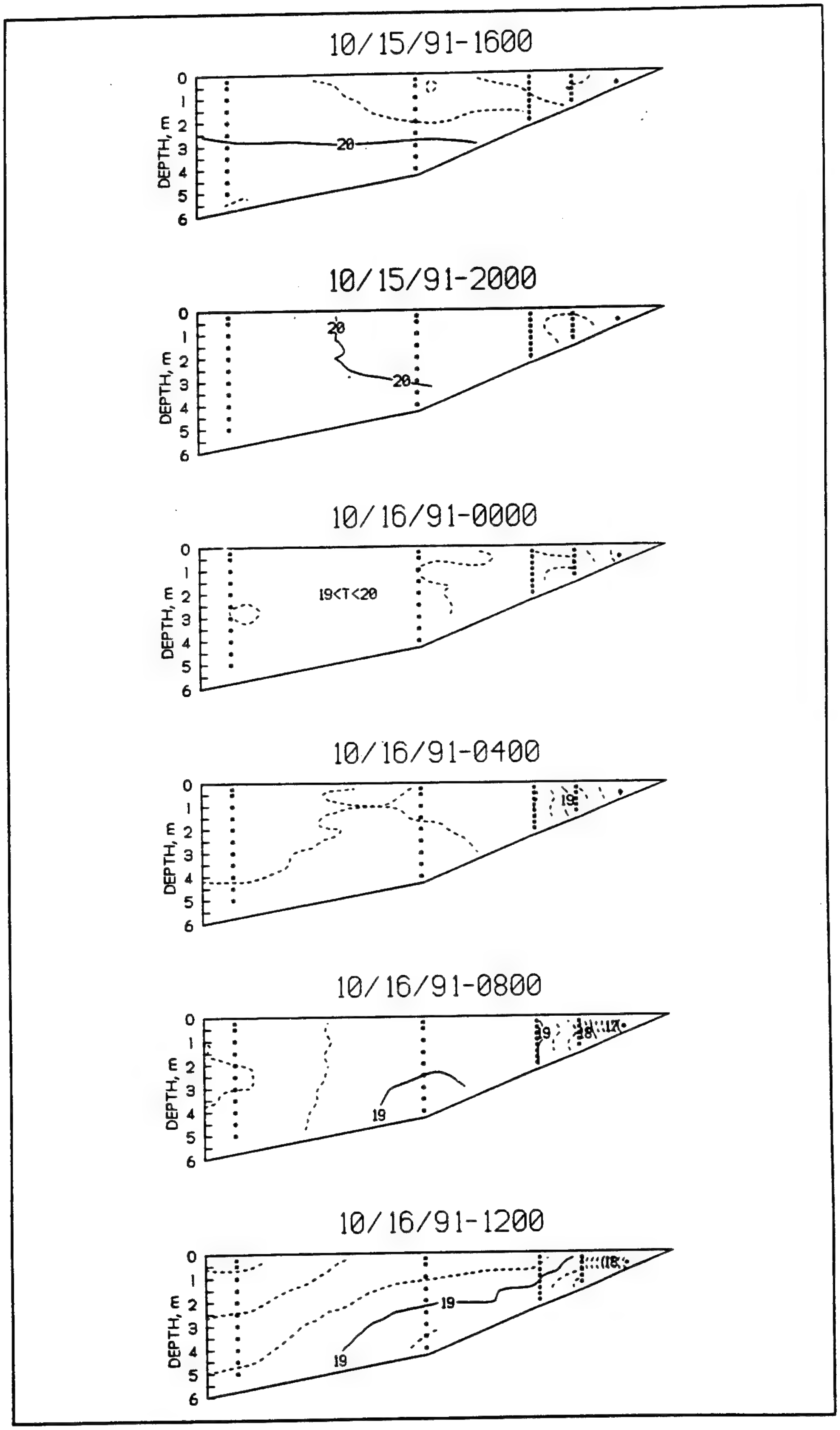

Figure 31. Water temperatures measured prior to and during October dye study

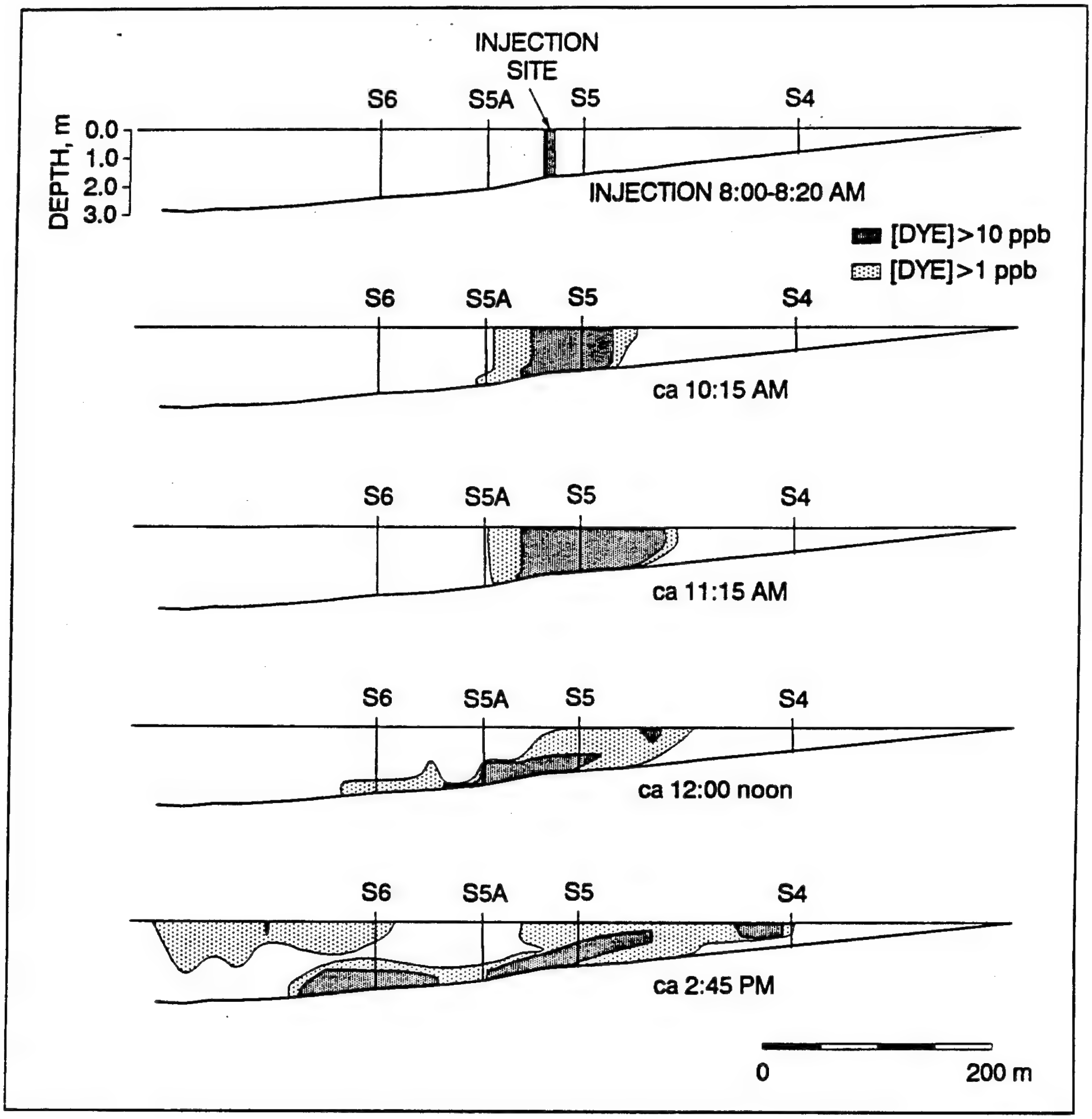

Figure 32. Movement of dye cloud along central transect, 16 October 1991

Discussion

Differential heating and cooling of the water column occurred on a diel basis nearly every day during the study period, indicating that convective circulation is potentially a very important hydraulic exchange mechanism in the Minky Creek embayment. Heating and cooling were often sufficient to greatly alter vertical and horizontal temperature gradients, as shown by regular shifts between temperature patterns during most 24-hr periods.

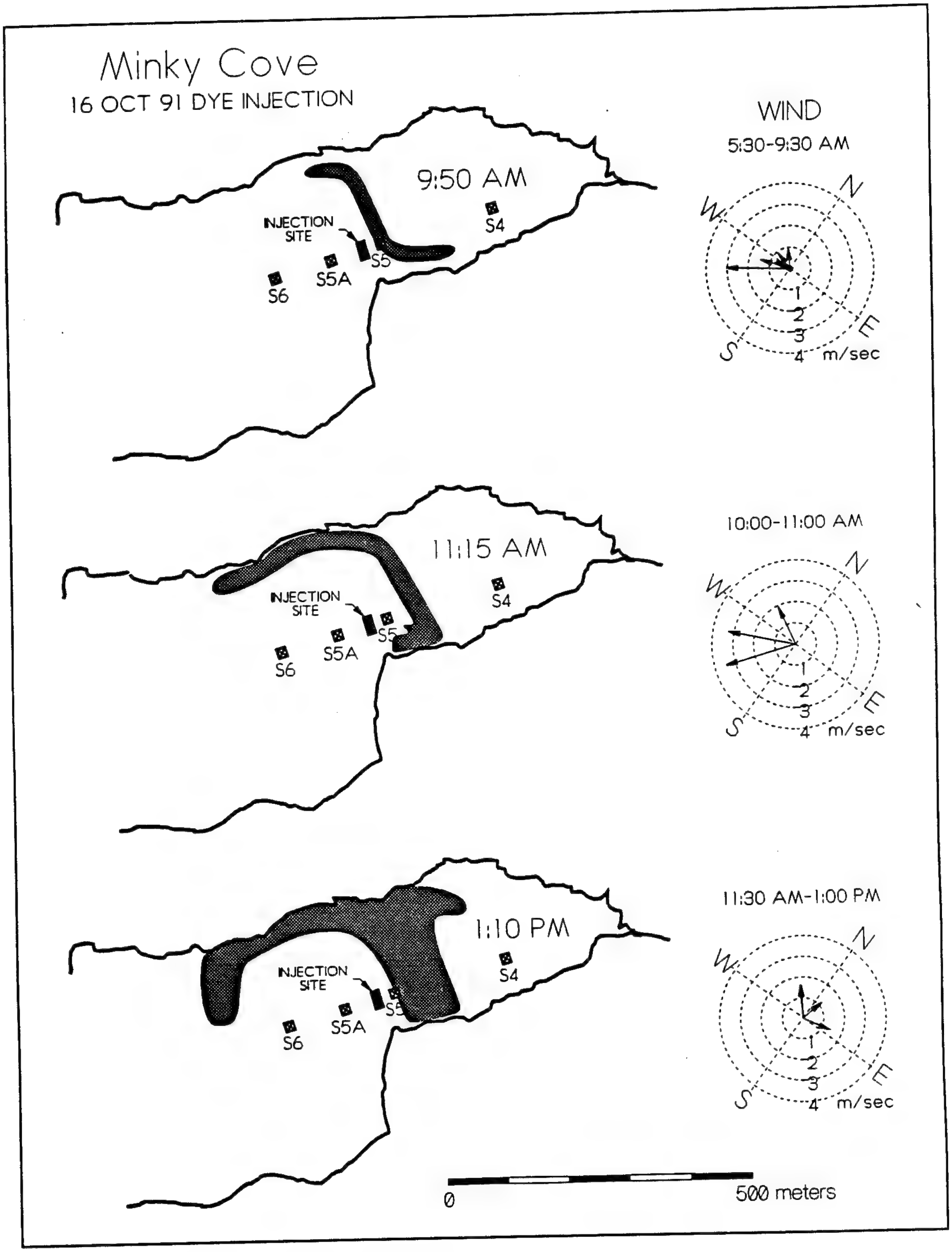

Figure 33. Movement of surface dye cloud and wind direction and velocity during morning and early afternoon of 16 October 1991 (Each wind arrow indicates average direction and magnitude of surface winds during 30-min period ending at indicated time. See Figure 21 for an explanation of wind indicators)

On sunny days, heating of surface water typically produced very strong thermal gradients. Shallow areas often became much warmer than even the surface layers at deeper locations. Substantial heating often extended to the bottom in shallow areas, though it was restricted to relatively shallow layers in deeper areas. Wind disrupted vertical stratification and deepened the surface mixed layer. On calm days, temperature gradients of 1 °C/m or greater developed within 0.25 m of the surface. On windy days, such vertical temperature gradients were absent from most or all stations. The depth of the late afternoon (1600 hr) mixed layer at Station 8 was related most strongly to winds over the previous 8 hr, or approximately the length of the daytime heating period.

Compared with vertical gradients, horizontal gradients develop over much greater distances and integrate past conditions over a longer time scale. Where the vertical extent of the late afternoon mixed layer was determined by conditions during the day of measurement, the intensity of horizontal temperature gradients was at least partially determined by temperature gradients and winds from the previous day.

Convective circulation typically lags behind the heating and cooling that produce it because of the inertia of the water masses involved (Monismith, Imberger, and Morison 1990). Thus, circulation produced by heating continues well into the night, and circulation produced by cooling continues into the afternoon. Dye injection results illustrate the persistence of circulation produced by nighttime cooling, which was still evident in the movement of dye masses at 1400 hr.

Results of the dye tracer experiment also illustrate the complex, three-dimensional circulation patterns produced by the combined effects of convection and wind. Convection-driven circulation, driven by nighttime cooling, moved surface water towards shore and deeper water outward along the bottom of the embayment. Surface water layers were also influenced by wind and responded rapidly to changes in wind direction. Wind moved surface layers laterally along the periphery of the embayment and eventually outward towards the mouth of the bay. Overall this wind-driven dye mass moved outward at velocities exceeding those produced by convection.

Differential heating promotes water circulation primarily in the upper 2 to 3 m of the water column because of warm surface flows that develop when there is a relatively shallow mixed layer. During differential cooling, water moves from shallow regions as underflows and is replaced with a return current of surface water. Thus, convective water circulation is relatively shallow during differential heating phases, whereas water located near the surface during the day potentially moves to the bottom of the embayment at night during differential cooling phases. These fundamentally different circulation patterns have important implications for the transport and availability of nutrients to phytoplankton communities located in the euphotic zone (James and Barko 1991a,b). They may also play an important role in determining the fate of aquatic herbicides.

How the convective flow velocities measured during the single dye study relate to those that develop under other environmental conditions is not currently known. Flow velocities appear to be driven by the intensity of horizontal temperature gradients. Linden and Simpson (1986) showed experimentally that under calm conditions, convective flows are generated as a result of a sharpening of horizontal temperature gradients, or frontogenesis, and that turbulence (i.e., wind mixing) can arrest or reduce convective flow velocities by disrupting these fronts. Thus, flow velocities may be strongly affected by wind mixing. In addition, it is often difficult to separate wind-generated circulation patterns from those generated by differential heating and cooling on the basis of water temperature alone (i.e., Monismith, Imberger, and Morison 1990).

In the absence of wind mixing, factors influencing light extinction, such as turbidity, can strongly affect the development of the mixed surface layer and convective circulation dynamics. Aquatic macrophytes both dampen wind effects and substantially reduce light penetration into the water column, resulting in the development of a very shallow (i.e., 25 cm or less) surface mixed layer. Shallow heat penetration prevents warming of the bottom waters in shallow regions, which may inhibit daytime convective circulation (Imberger and Patterson 1990). Resultant horizontal temperature gradients that develop may therefore provide an insufficient baroclinic pressure gradient (i.e., Monismith, Imberger, and Morison 1990) to allow for convective circulation during the day. Since nighttime cooling is penetrative, it may be relatively unaffected in vegetation, or may be stronger because of reduced wind effects. Thus, circulation patterns may differ significantly between vegetated and unvegetated areas.

5 Studies of Water Movement in the Mud Creek Embayment of Guntersville Reservoir[1]

Introduction

In 1993, studies of hydraulic circulation were moved upstream from Minky Creek to the Mud Creek embayment. This location provided an opportunity to examine water circulation in more sheltered, vegetated locations. Two sites varying in exposure were selected, one in a small cove and the other located along an open section of shoreline. Both sites contained dense beds of submersed macrophytes.

This chapter describes the results of dye injection studies of water movement and water temperature measurements in the two Mud Creek sites.

Methods

Site description

The Mud Creek embayment of Guntersville Reservoir is a drowned creek valley located near the middle of the reservoir (Figure 34). Temperature monitoring and dye movement studies were conducted in two locations within the embayment (Figure 35). One study site (cove) was a small cove on the east side of the embayment; the other (open) was in an extensive aquatic plant bed located off a relatively exposed portion of the west shore of the embayment. Both sites were vegetated with dense beds of *Myriophyllum spicatum* at water depths from approximately 0.5 through 2.0 m.

[1] Chapter 5 was written by Craig S. Smith, Harry L. Eakin, and John W. Barko.

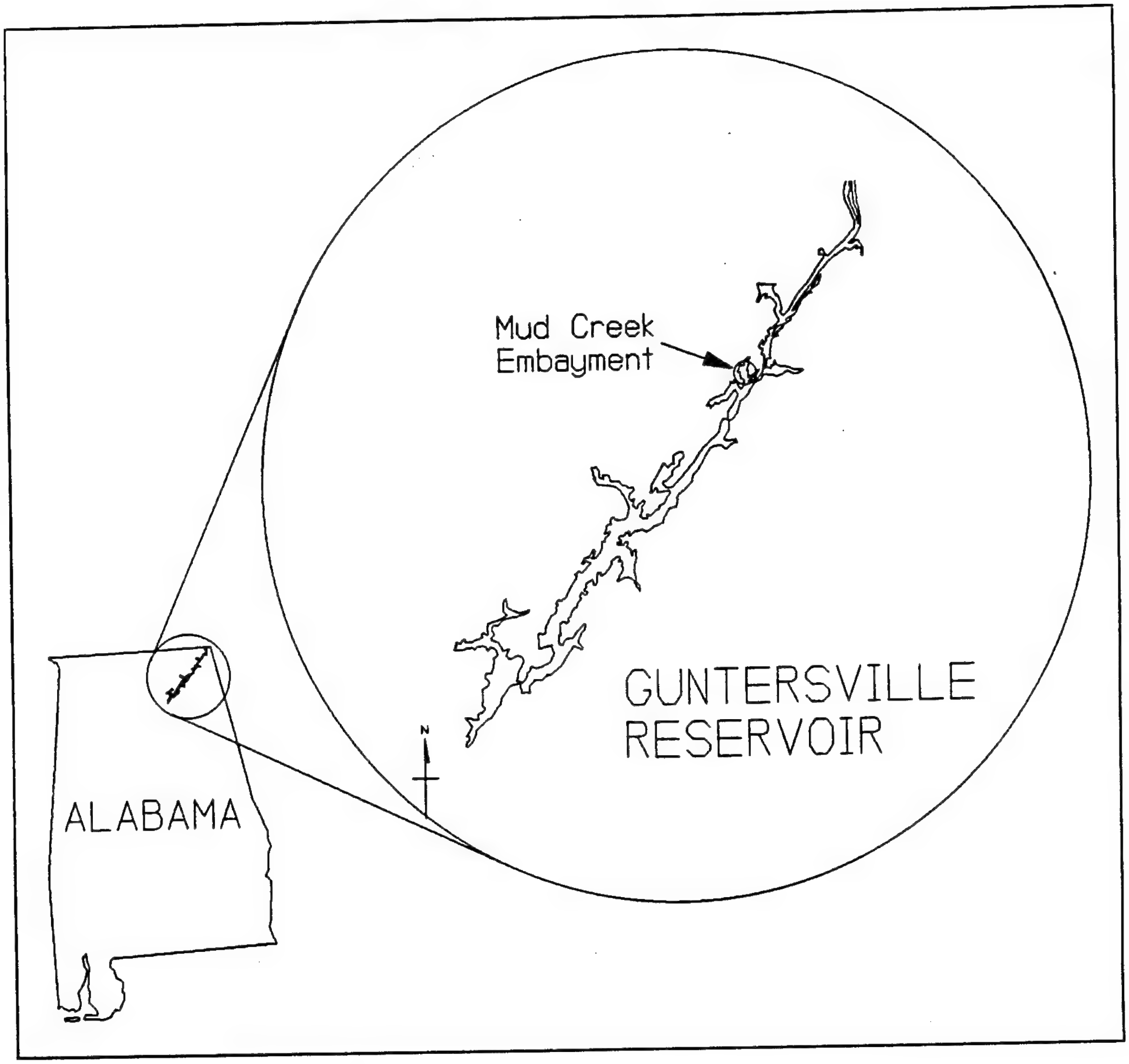

Figure 34. Location of Guntersville Reservoir and Mud Creek Embayment

Temperature and meteorological measurements

Temperature and meteorological recording stations were established within each area (Figure 35). In the cove site, temperature stations formed a transect extending down the approximate centerline of the cove to a point just outside the mouth of cove. In the open site, the stations were arranged perpendicular to the shore, with the outermost station at the outer edge of the vegetation. At each temperature recording location, water temperatures were recorded every 30 min at 0.25-m-depth intervals. At one station in each site, wind speed and direction were measured every 5 min, and vector averages of both were recorded at 30-min intervals. Air temperature, relative humidity, and solar irradiance were recorded at one location in the cove every 30 min. A water level gauge recorded the water surface elevation every 30 min at a central

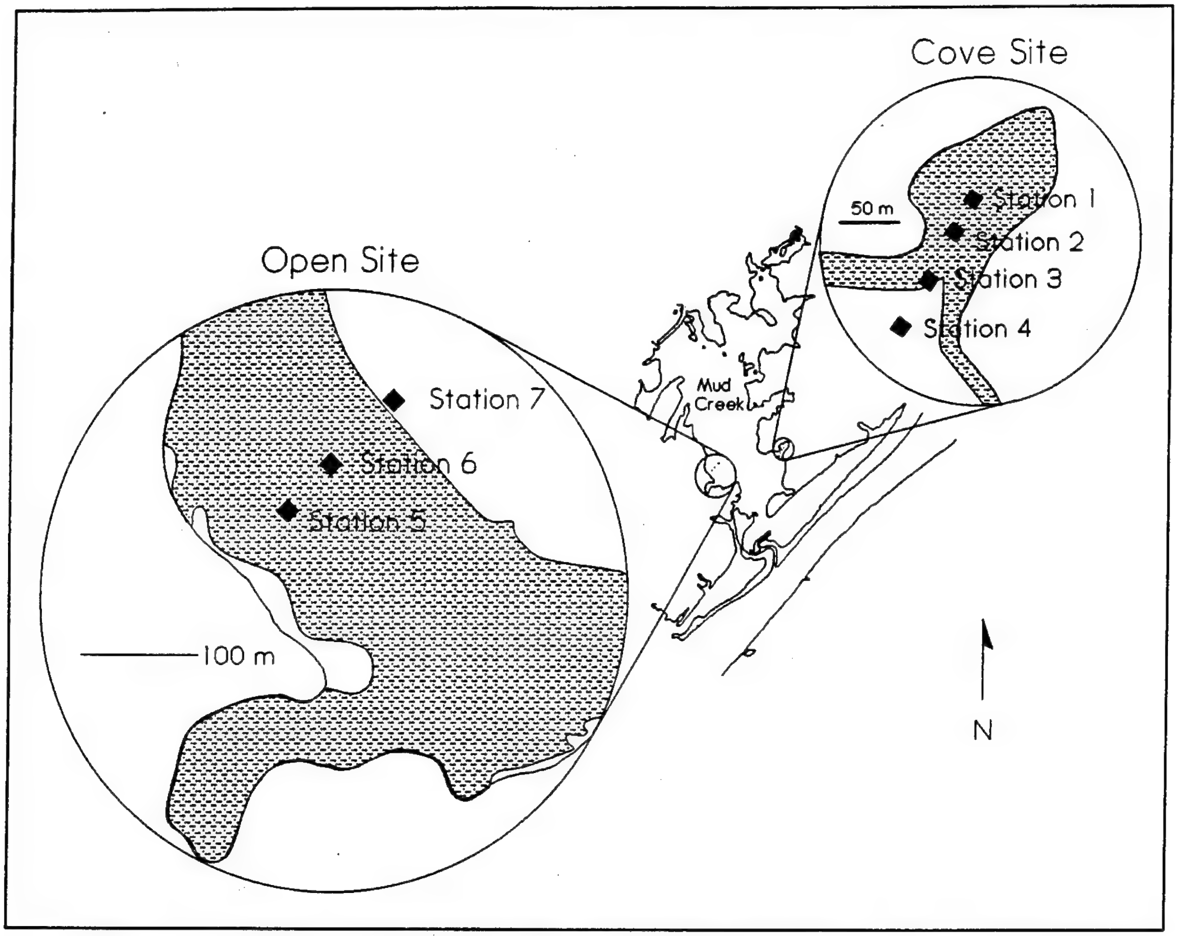

Figure 35. Map of Mud Creek Embayment of Guntersville Reservoir, showing locations of temperature and meteorological recording stations in cove and open sites (All stations recorded water temperatures; weather stations were located at Stations 2 (wind and irradiance) and 7 (wind, air temperature, and relative humidity), and Station 3 recorded water elevations. Shading indicates the extent of submersed plant coverage)

location in the cove site. Temperature and other measurements were recorded from May 27 until November 8, 1993.

Dye studies

Water movement in the two study sites was measured by injecting Rhodamine WT fluorescent dye into the water column and tracing the movement of the injected dye. Prior to injection, concentrated dye was mixed with methanol in a 2:1 ratio (dye:methanol), producing a mixture with a density of 1.0 g/cm^3. The dye-methanol mixture was introduced into the water column by injecting 19 to 60 ml of the mixture into a loop of vinyl tubing through which a peristaltic pump was pumping lake water up from and back to the intake depth. During injection, the ends of the pump tube were moved up

and down through the water column to mix the dye as evenly as possible from top to bottom.

Following the injection of dye into the water column, dye concentrations throughout the sample site were monitored for 3 to 6 hr. Dye concentrations were measured with a Turner designs fluorometer. Dye sampling locations were chosen in the field based on observed dye movement and dispersion.

Rates of water movement were calculated from dye concentration measurements by examining the movement of the center of mass of the dye cloud. The location of the center of mass was calculated as the three-dimensional concentration-weighted average of dye measurements. For this calculation, dye concentration measurements were lumped into time intervals such that each group included sufficient measurements to cover the spatial extent of the cloud. The resulting time intervals varied from approximately 0.5 to 3.5 hr, depending on the size of the cloud and the intensity of sampling. Since surface and deeper layers tended to move independently, the locations of the dye cloud center of mass were calculated separately for surface (typically <1.0 m) and deeper (typically $\geq$1.0 m) water masses. When it was clear from the spatial distribution of measured dye concentrations that a portion of the dye cloud had been missed by the sampling, the center of mass was assumed to occur in the location with the highest dye concentration.

Results

Cove site

In the cove site, dye moved primarily along the transect axis, so analysis of water movement in the cove concentrates on movement along this axis. On all dates examined, patterns of water movement were relatively consistent (Figure 36), particularly for water on the bottom of the cove. Prior to 1100 hr, water on the bottom of the cove moved toward the back of the cove, usually at a moderate rate. After approximately 1100 hr, bottom water moved rapidly out toward the mouth of the cove.

Surface water movement was somewhat more variable. Generally, surface water moved back into the cove at a moderate rate prior to 1000 or 1100 hr, after which it slowed down and the direction of movement varied. After approximately 1800 hr, the direction of surface water movement reversed, and it moved towards the mouth of the cove.

The velocity of surface water movement ranged from 0.1 to near 5 mm/sec (Table 3). Lower velocities (<1.0 mm/sec) were typically associated with reversal of flow. Movement of water on the bottom of the cove was more rapid, particularly when in the direction of the cove mouth, with velocities typically ranging from 0.8 to near 10 mm/sec. During one time interval, a velocity of 20.3 mm/sec was recorded.

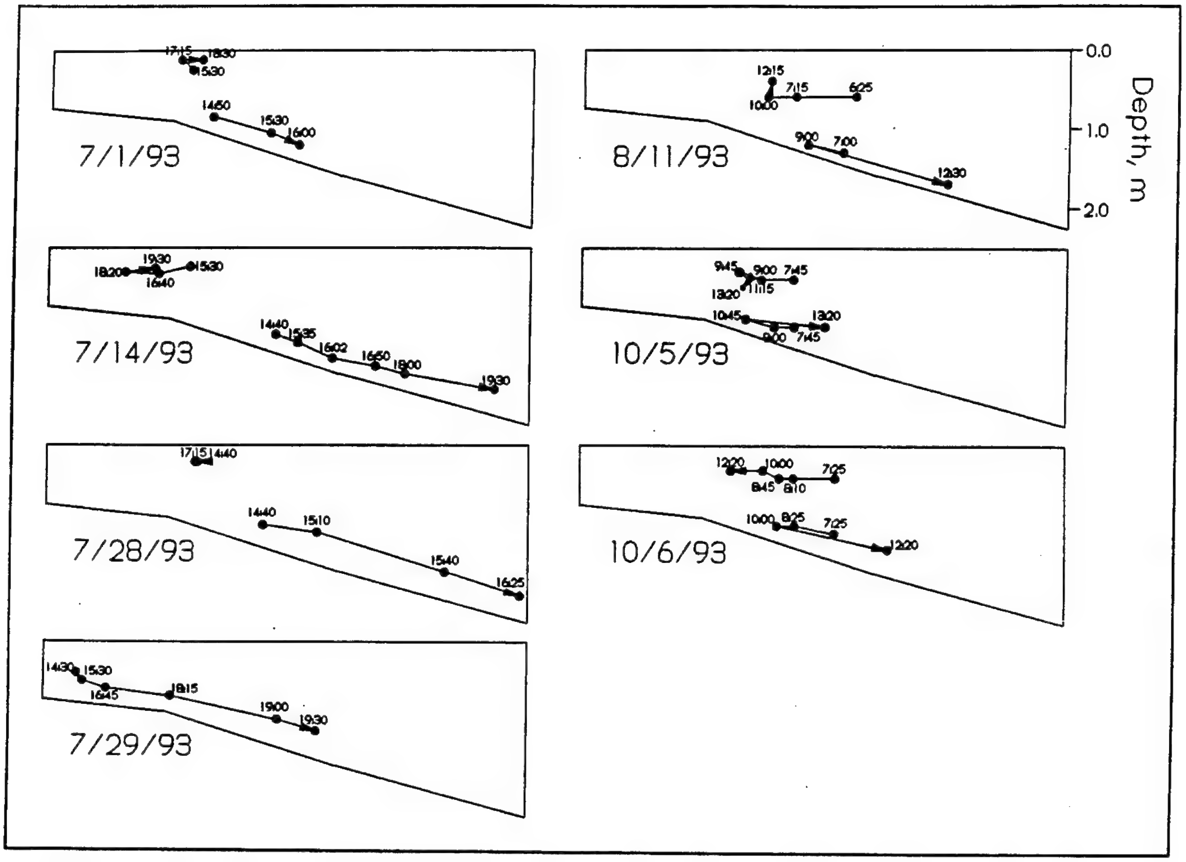

Figure 36. Movement of centers of mass of injected dye clouds in cove site

Water levels in the Mud Creek Embayment fluctuate up to 20 cm in a 24-hr period, as the result of operational activities at the Nickajack Dam (upstream). During these dye studies, turbines at Nickajack Dam were typically operated to produce electricity from approximately 0700 hr until midnight, with peak flows lasting from 0800 until 2200 hr. At the Mud Creek site, this schedule produced a cycle of rising water levels from approximately 0600 hr until around 1000 or 1100 hr and falling water levels from then until the following morning. Four of the dye studies in the cove were conducted during the afternoon and evening, while water levels were falling, and the remaining two studies were conducted in the morning and early afternoon, as water levels rose, peaked, and then fell (Figure 37).

There was a strong correspondence between water level changes and the direction and rate of water movement in the cove. As water levels rose, both surface and bottom water moved towards the rear of the cove. After the peak, as water levels began to fall, water on the bottom switched directions almost immediately and began to move rapidly outward. Surface water movement slowed as water levels began to recede, but surface water did not begin to move outward until water levels had been dropping for several hours.

Table 3
Movement of Centers of Mass of Dye Clouds in Cove Site

Date	Shallow, <1.0 m			Deep, ≥1.0 m		
	Time[1]	Velocity mm/sec	Direction[2]	Time[1]	Velocity mm/sec	Direction[2]
1 July	15:45	1.1	IN	15:30	5.4	OUT
	17:15	0.5	IN	16:30	2.1	OUT
14 July	15:30	2.6	IN	15:35	5.2	OUT
	16:40	1.9	IN	16:00	5.3	OUT
	18:20	1.5	IN	16:50	3.7	OUT
	19:45	1.5	IN	18:00	1.9	OUT
28 July				19:30	4.4	OUT
	14:40	3.0	IN	14:35	9.7	OUT
	15:15	1.4	IN	15:10	6.4	OUT
	17:15	0.1	OUT	15:40	20.3	OUT
				16:25	7.3	OUT
				17:15	1.7	IN
29 July				15:30	2.0	OUT
				16:45	1.4	OUT
				18:15	3.2	OUT
				19:05	9.4	OUT
11 August	06:20	0.2	IN	07:00	1.0	IN
	07:20	4.7	IN	09:30	1.0	IN
	10:00	0.7	IN	12:30	3.4	OUT
	12:15	0.1	OUT			
5 October	08:00	4.4	IN	08:00	4.3	IN
	09:00	2.3	IN	09:00	1.4	IN
	09:45	2.1	IN	10:45	1.2	IN
	10:30	0.1	IN	13:20	2.2	OUT
	11:30	0.7	OUT			
	13:20	0.2	IN			
6 October	07:25	1.7	IN	07:25	1.7	IN
	08:10	4.2	IN	08:25	3.0	IN
	08:45	1.6	IN	10:00	0.8	IN
	10:00	0.9	IN	12:20	3.4	OUT
	12:20	1.0	IN			

1 Midpoint of time interval.
2 IN describes movement towards head of cove. OUT describes movement towards mouth of cove.

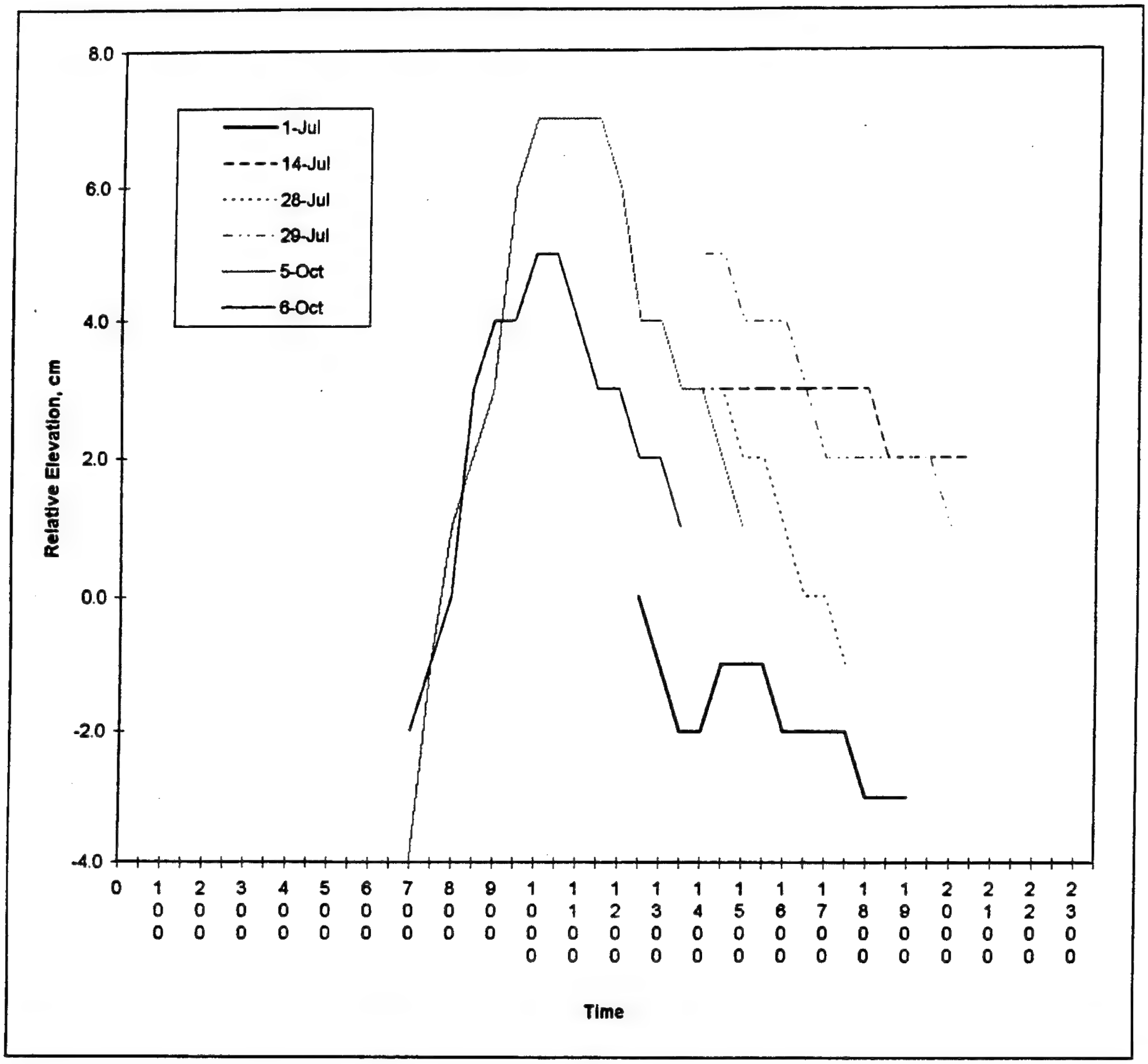

Figure 37. Water level fluctuations during dye studies in cove site

Temperature patterns in the cove reflected the retention of surface water toward the back of the cove while bottom water drained outward, as shown in temperature patterns from July 1 (Figure 38). Heating during the day produced a very warm layer of water on the surface. Instead of flowing outward as it would in the case of convective circulation, warm surface water was retained in the cove as water levels fell. The result was a zone of warm temperatures on the surface that receded towards the back of the cove as the afternoon and evening progressed. The retention of warm water in the back of the cove led to very high temperatures. Surface temperatures in excess of 30 °C were recorded on 41 days, and temperatures in excess of 40 °C were recorded on 2 days.

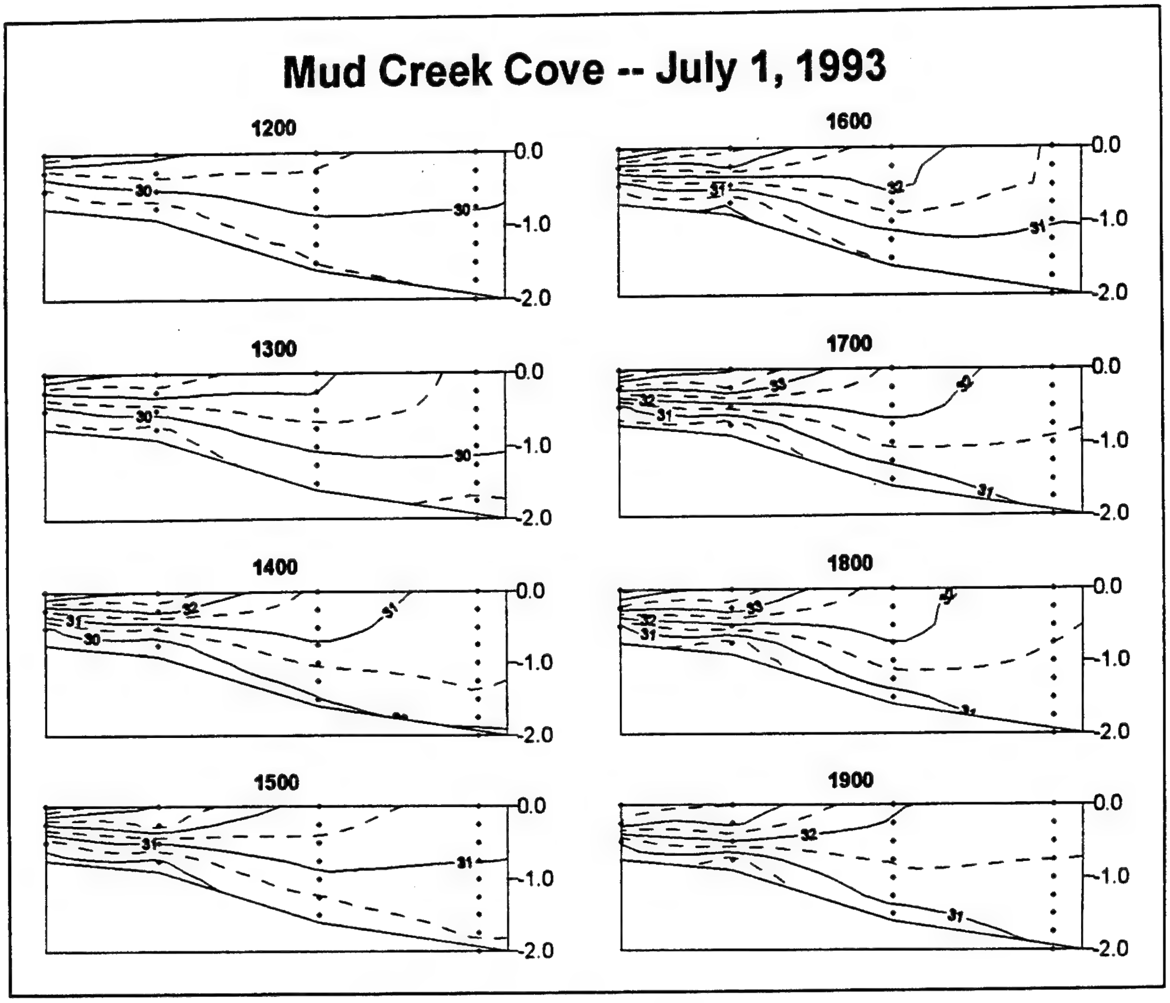

Figure 38. Temperature patterns in cove on July 1, 1993

Open Site

In the open site, water movement rates and patterns were highly variable (Table 4). The direction of water movement was not at all consistent from study to study and often changed during the course of a single study. Surface and bottom water masses typically moved in different directions. The velocity of water movement was typically somewhat slower than in the cove site, with near-surface velocities ranging from 0.4 to nearly 10 mm/sec and near-bottom velocities ranging from 0.6 to 3.5 mm/sec.

In this location, most of the studies were conducted during periods of little water level change (Figure 39), and effects of reservoir operation were not usually discemable. One exception to this generalization was the dye injection study on October 7, during which water levels rose 5 cm during the first 2½ hr of the study and then fell 4 cm during the last 3 hr. In this study, surface and bottom water masses moved in a pattern similar to that observed in the cove site (Figure 40). As the water level rose, both surface and bottom water

Table 4
Movement of Centers of Mass of Dye Clouds in Open Site

		Shallow, <1.0 m		Deep, ≥1.0 m	
Date	Time[1]	Velocity mm/sec	Direction deg	Velocity mm/sec	Direction deg
13 July	16:20	1.1	345	1.0	100
	17:50	1.1	90	1.5	346
15 July	14:50	9.9	267		
	15:30	4.4	317		
	16:50			1.8	30
27 July	15:20	0.9	231		
	17:35	3.0	270	0.8	288
10 August	15:15	1.8	81	0.6	81
	16:45	8.2	122	0.7	270
12 August	15:00			2.2	54
	16:15			1.7	56
	Overall	0.5	343		
7 October	07:30			3.5	325
	08:20			1.0	314
	09:20	1.0	346	1.6	93
	10:30	0.4	270		
	11:40	1.9	332	3.4	94

[1] Midpoint of time interval.

masses moved in a direction that was approximately upstream. As the water level began to fall, movement on the surface continued in the same direction as before, but the bottom water mass changed direction and began to move back towards the mouth of the creek.

Wind and convection were also evaluated as possible causes of the observed water movement, but no simple relationships were detected. The direction and velocity of water movement were not correlated with wind direction and velocity.

Discussion

Water exchange in the cove site was considerably more rapid than might be expected in a small isolated cove. Water level fluctuations from the operation of Nickajack Dam produced relatively rapid water exchange and a consistent

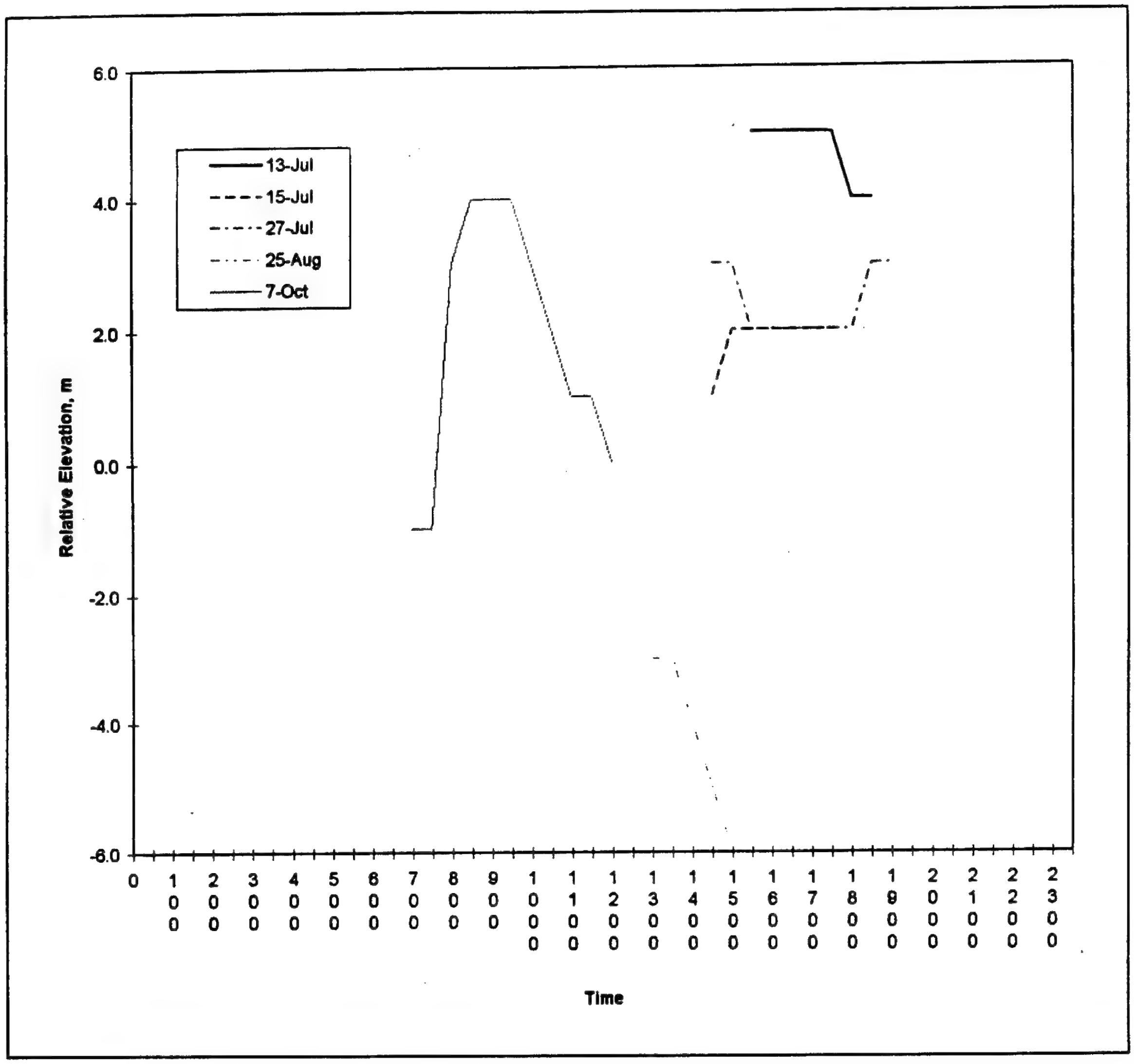

Figure 39. Water level fluctuations during dye studies in open site

daily pattern of water movement in this location. Rising water levels pushed both surface and bottom water back into the cove. As water levels began to recede, water on the bottom of the cove drained rapidly outward. The water on the surface continued to move slowly, usually towards the back of the cove. When water levels retreated during the afternoon, this pattern of water movement caused warm surface water to be retained in the back of the cove, rather than flowing outward as it would if water circulation were dominated by convection. The resulting surface water temperatures in the back of the cove were very high, frequently exceeding 30 °C and occasionally exceeding 40 °C.

Patterns of water movement in the open site were complex and generally showed no apparent relationship to any of the mechanisms investigated (i.e., wind, convection, or reservoir operation). The lack of a relationship between water movement and wind is not surprising since a previous study at this site determined that water currents were correlated with the direction of the wind

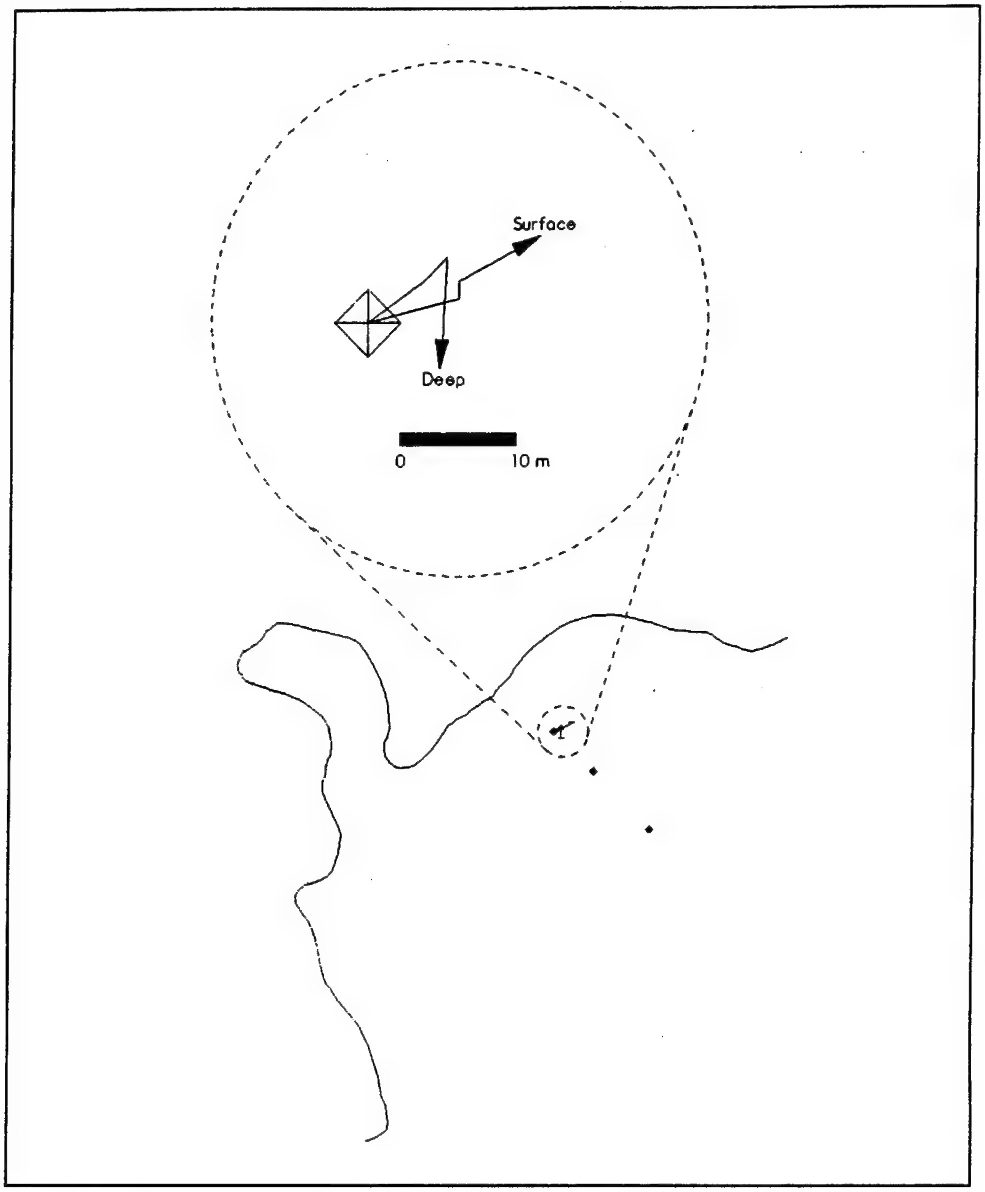

Figure 40. Movement of centers of mass of shallow (<1.0 m) and deep (≥1.0 m) dye clouds in dye study conducted October 7

only when wind speed exceeded 2.0 m/sec (Smith, unpublished). Wind speeds were below that during the dye studies reported herein. The effects of reservoir operation on water movement in this site are probably substantial, but all but one of the dye studies in this location were conducted during periods of little water elevation change. Effects of reservoir operation were evident in the one study during which water level fluctuations were large.

Effects of macrophytes on water movement were not evident in either site. Both sites contained beds of *Myriophyllum spicatum*, which formed a dense canopy at the surface. Losee and Wetzel (1993) found that water movement in a *Scirpus subterminalis* bed tended to be most rapid near the bottom,

presumably because of the presence of less plant surface area in that stratum. In the cove site, movement of bottom water was found to be more rapid than movement of surface water, but only when water levels were declining. When water was being forced into the cove by rising water levels, surface water moved at velocities comparable with bottom water. In the open site, rates of movement of surface water were comparable or slightly higher than rates of bottom water movement.

The patterns of water movement disclosed by this study have important implications for the transport of dissolved materials. The daily, rapid movement of bottom water out of the cove has the potential to carry with it any nutrients, herbicides, or other dissolved materials. Given the observed daily flow patterns, herbicide formulations sinking into the bottom waters during the early afternoon would be rapidly removed from the cove. For these formulations, contact time would be very limited as would the likelihood of successful control. In contrast, formulations remaining near the surface would be retained in the cove for a considerably longer period.

Conclusions

A number of general conclusions can be drawn from the studies reported herein. First, water in aquatic macrophyte beds is far from stagnant. Flow in macrophyte beds is often slow, but sufficient to exchange water in littoral areas one or more times per day. Even when submersed macrophytes are present and might be expected to dampen the transfer of wind energy and retard water circulation, other mechanisms can drive water circulation in shallow regions.

In Eau Galle Reservoir, convection because of nighttime cooling is a very important mechanism moving water through plant beds and into open-water areas of the reservoir. During periods of cooling-driven convection, the residence time of water in plant beds is on the order of 1.0 day (see Chapter 2). Movement of cool water out along the bottom of the littoral zone transports with it phosphorus released from sediments, which is carried into the pelagic zone (James and Barko 1991a,b). Convectively driven circulation is particularly important in Eau Galle Reservoir, because the reservoir is relatively small and sheltered from the wind, is located in a climate where there is considerable nighttime cooling in the summer, and reservoir elevations fluctuate very little except following storms.

Wind-driven circulation was much more important in the larger, more exposed Minky Creek Embayment of Guntersville Reservoir, but conditions likely to produce convective circulation were detected nevertheless. Differential heating and cooling of the water column occurred nearly every day, indicating that convective circulation is potentially very important. Unlike Eau Galle Reservoir, conditions for exchanges during differential cooling in the Minky Creek Embayment predominated only when the water column exhibited a net daily heat loss. Strong nighttime differential cooling during periods of net gain was rarely detected. In contrast, periods of net daily heat gain in the

water column led to convective exchanges because of differential heating. These results suggest that convective exchange may be regulated, in part, by longer term general warming and cooling trends. More detailed information is needed over an entire season to better understand the effects of weather trends on convective water exchange.

Wind can influence convectively driven flow in a number of ways. Flow velocities appear to be driven by the intensity of horizontal temperature gradients. Linden and Simpson (1986) showed that turbulence (e.g., from wind mixing) can arrest or reduce convective flow velocities by disrupting horizontal temperature gradients. Thus, flow velocities may be strongly affected by wind mixing. Wind also influences convective circulation by regulating the depth of the surface mixed layer, and thus, the distribution of heat in the water column. Periods of relatively strong daytime heating in conjunction with wind-generated mixing, appear to result in the distribution of heat to deeper depths, thereby promoting the development of a vertically expansive overflow during convective exchange. With little wind-generated mixing, surface water heating is very shallow (on the order of a few centimeters) during differential heating phases in the Minky Creek embayment. Thus, convective water exchanges are probably taking place in a very thin surface layer under these conditions.

Changes in water elevation because of reservoir operation drove relatively rapid water exchange in the Cove site of Mud Creek in Guntersville Reservoir. Water level fluctuations from the operation of Nickajack Dam dominated other potential circulation mechanisms and produced a fairly consistent daily pattern of water movement in the cove. Rising water levels pushed both surface and bottom water back into the cove. Receding water levels caused cooler water to drain out rapidly along the bottom of the cove, while surface water was typically retained in the back of the cove. Retention of warm water in the back of the cove led to very high surface water temperatures there.

In these studies, specific effects of submersed macrophytes on water circulation were not detectable. Losee and Wetzel (1993) suggested that lowered plant resistance near the bottom, because of the presence of less plant surface area in that stratum, allowed more rapid flow rates there. Although the effect they suggest is likely, several of the mechanisms investigated produced more rapid flows near the bottom for reasons that did not involve flow resistance of vegetation. Carefully controlled experimental studies that manipulate plant density would be necessary to detect effects of plant biomass on water circulation.

The patterns of water movement disclosed by these studies have important implications for the transport of dissolved materials. Even in the complete absence of wind, the residence time for water in plant beds can be low because of convection and other exchange mechanisms. Thus, herbicide application strategies must consider both short residence times and the types of circulation produced by these alternate mechanisms. When bottom waters are moving rapidly out of the littoral zone, sinking herbicide formulations would be rapidly removed from plant beds. Thus, contact time would be very limited as would

the likelihood of successful control. The fate of formulations remaining near the surface would depend on the circulation pattern. Convective circulation driven by heating would rapidly remove such a formulation while receding water levels would tend to retain it for a considerably longer period. Horizontal movement of water may also transport soluble nutrients originating from decaying macrophytes or sediment release to the pelagic zone and thereby stimulate undesirable algal blooms.

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Craig S. Smith, William F. James, John W. Barko, and Harry L. Eakin

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13. ABSTRACT *(Maximum 200 words)*

Temperature and water exchange patterns were examined in several vegetated and unvegetated littoral areas in Eau Galle Reservoir, Wisconsin, and Guntersville Reservoir, Alabama. Water temperatures and movement of injected dye were examined to determine rates of water movement and to identify the forces driving water exchange in these areas.

Convective circulation because of nighttime cooling was particularly important in Eau Galle Reservoir, where the study site was a small, sheltered embayment on a small reservoir. Differential cooling of shallow areas led to movement of cool water along the bottom of the littoral zone and into the pelagic zone, while warmer water moved toward the shore along the surface.

Temperature patterns indicative of convective circulation were also observed in the much larger, more exposed Minky Creek Embayment of Guntersville Reservoir. Differential heating and cooling of the water column sufficient to produce horizontal temperature gradients necessary for convective circulation occurred frequently. Effects of wind were also evident, both in terms of generating water currents and as an influence on the temperature gradients that developed during heating and cooling. The depth of the late-afternoon mixed surface layer was positively correlated with the average wind velocity during the previous 8 hr. Wind also disrupted horizontal temperature gradients, thereby reducing the impetus for convective circulation.

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Water movement in the Mud Creek Embayment of Guntersville Reservoir was dominated by effects of the operation of Nickajack Dam upstream. Changes in the discharge rate from the dam led to daily fluctuations in water elevation. Effects of changing water levels were most pronounced in a study site located in a small isolated cove, where they drove a predictable daily pattern of water circulation. Effects of water level changes were sometimes detectable in a second more open site, but in this location they were often overcome by other driving forces.

These results illustrate several mechanisms that can produce water movements in shallow regions of reservoirs. These circulation patterns, occurring on a daily basis, may transfer nutrients and influence phytoplankton productivity. They also need to be considered in planning and scheduling herbicide applications.